This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.
+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.
+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.
+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

TUNNELING

McGraw-Hill Book Company

Publishers of Books for

Electrical World
The Engineering and Mining Journal
Engineering Record
Engineering News
Railway Age Gazette
American Machinist
Signal Engineer
American Engineer
Electric Railway Journal
Coal Age
Metallurgical and Chemical Engineering
Power

TUNNELING

SHORT AND LONG TUNNELS OF SMALL AND LARGE SECTION DRIVEN THROUGH HARD AND SOFT MATERIALS

BY

EUGENE LAUCHLI

CIVIL ENGINEER

MEMBER AMERICAN INSTITUTE OF MINING ENGINEERS

FIRST EDITION

NEW YORK
PUBLIC
LIBRARY

McGRAW-HILL BOOK COMPANY, INC.
239 WEST 39TH STREET, NEW YORK
6 BOUVERIE STREET, LONDON, E. C.
1915

THE NEW YORK
PUBLIC LIBRARY
702538
ASTOR, LENOX AND
TILDEN FOUNDATIONS
R 1915 L

COPYRIGHT, 1915, BY THE
McGRAW-HILL BOOK COMPANY, INC.

THE MAPLE PRESS YORK PA

PREFACE

The preparation of this treatise on tunneling was undertaken as an endeavor to supply practicing engineers and contractors with such information as is needed most usually in tunnel work, and to present students with the underlying principles indispensable to the solution of the many problems met with in driving tunnels serving miscellaneous purposes.

It is no small task to give, within the scope of this book, all such information as may be expected by tunnel men in general; such subjects as drilling machinery and equipment, compressor and ventilating plants, explosives and their use, etc., which alone would make a book, together with bulky descriptions bearing on the driving of individual tunnels, have necessarily been avoided or dwelt upon only briefly, and the text has been reduced to a minimum.

On the other hand, a serious effort has been made to illustrate the various subjects treated, or the theories developed, by practical examples and figures, taken from actual practice.

This work is composed to a large extent of results of personal observations and studies, together with data collected from direct and reliable sources. In several cases, however, material has been taken from various technical papers and other contributions. Several of the subjects contained herein have already been presented by the writer, in a modified or abridged form, in technical papers during recent years. These subjects have been rewritten, corrected when necessary, or modified so as to accord with present practice, or new theories developed. All matter pertaining to the cost of long tunnels, as driven in foreign countries, has been omitted, as it is practically impossible to compare the cost of bores driven in this country and abroad, owing to the difference in labor available, and in the wages prevailing and also in the needs and requirements of this and other continents.

The writer wishes to express his indebtedness to Messrs.

Clemens Herschel, Consulting Engineer; W. L. Saunders, President of the Ingersoll-Rand Co., and S. P. Brown, Chief Engineer of the Mount Royal Tunnel and Terminal Co. Ltd. Also to the General Direction of the Swiss Federal Railroads and to the Bernese Alps R. R. Co., as well as to many other engineers and contractors, for their kind assistance in furnishing information or data in connection with this book.

E. L.

NEW YORK, 1914.

NEW YORK PUBLIC LIBRARY

CONTENTS

		Page
Preface		v
Introduction		ix
Chapter		
I.	Importance of Geological Surveys in Connection with Tunnel Driving	1
II.	Headings and Tunnels of Small Cross Section. Driving Methods	9
III.	Haulage Methods	22
IV.	Tunnels of Medium Cross Section	31
V.	Railroad Tunnels of Moderate Length	45
VI.	Drilling Machinery Used in Connection with Tunnel Work	63
VII.	Long and Deeply Overlaid Tunnels	70
VIII.	Method of Handling and Removing Excavated Materials	85
IX.	Tunnel Timbering	94
X.—	Lining Deep Tunnels	108
XI.	Determination of the Rock Temperature in Deeply Overlaid Tunnels	120
XII.	Vitiation of the Atmosphere of Long Tunnels	145
XIII.	Ventilation During Construction of Long and Deep Tunnels	150
XIV.	Tunnels Driven Through Soft Materials	163
XV.	Pressure Acting on Tunnels Driven Through Soft and Cohesionless Materials	175
XVI.	Siphon Tunnels	185
XVII.	Tunnels Driven with Compressed Air	204
XVIII.	Miscellaneous Tunnels	218
Index		231

INTRODUCTION

The great improvement in tunneling methods and machinery made in the past decade is responsible for the large development that has taken place in the railroad world, in this and other countries. Mountain ranges, which heretofore had defied the railroad pioneer, are being pierced at their very base, and must yield to the slow but irresistible work of the tunnel driver.

In America, great undertakings such as the Catskill and Los Angeles aqueducts have been accomplished in record time. In the Alpine region, the Simplon and Loetschberg tunnels have proven that length, combined with great depth of overlay, are no longer insurmountable obstacles, and that a high rate of progress can be attained with the assistance of modern tunneling methods, machinery and proper organization. In the Jura mountains, no less than five tunnels, from 2 to 5 miles in length, have recently been driven. The Pyrenees, the natural barrier between France and Spain, have likewise been pierced by several long tunnels, and the Caucasus mountains are to be tunneled by a bore not less than 16 miles long.

It is but a question of a few years before the Rockies and other ranges will be pierced by long and deeply overlaid tunnels, serving the purpose of eliminating heavy grades, sharp curvature, and the necessity of reaching high altitudes under most adverse conditions.

TUNNELING

CHAPTER I

IMPORTANCE OF GEOLOGICAL SURVEYS IN CONNECTION WITH TUNNEL DRIVING

The data collected in driving tunnels, together with the progress of geological science, during the past half century, have enabled geologists to add to and perfect their knowledge, correct erroneous theories as to the origin and formation of mountain ranges and plateaus, thus prompting the tunnel engineer to recognize and appreciate more fully the value of geological researches and surveys.

The importance of geological surveys in connection with tunnel work was fully recognized already in 1853, when H. Gerlach undertook to study the geology of the Simplon Range, in view of the then projected base tunnel.

From that date, up to the completion of this bore, in 1906, no less than twelve geological profiles of the Simplon Range, by various authors, have been published, and the results obtained have thrown much light on that part of the Alpine region. The range penetrated by the Simplon tunnel has a very complex formation, the rock penetrated belonging practically to all ages of the geological scale, with folds of archean rocks, overlaying sheets of Jurassic formation, as shown by Fig. 1.

The prognosis of the geologists, with reference to the materials penetrated was remarkably true compared with that encountered, as shown in the following table:

Kind of material	Expected over a length of feet	Encountered over a length of feet
Calcareous schists, calcareous mica schists..	19,350	17,000
Crystalline limestone, marble, dolomite, gypsum, anhydrite.	4,430	4,580
Mica schists, crystalline schists.....	17,080	22,700
Monte Leone gneiss.	11,300	6,230
Antigorio gneiss	12,550	14,200

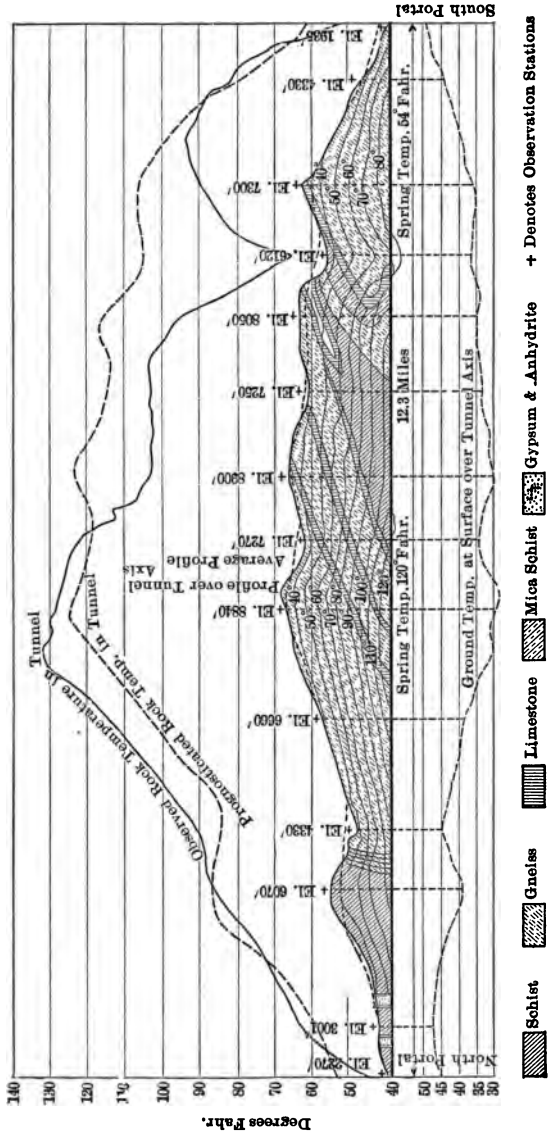


FIG. 1.—Geological profile of the Simplon tunnel showing distribution of rock temperature.

Location, Size and Number of Bores as Affected by Geological Considerations

The location of a tunnel, in a vertical plan, is a very complex problem, especially when piercing folded mountains, as for instance the Alps, Jura, Appalachians, Rockies, etc., owing to the fact that the strata of these ranges have been subjected at various epochs to enormous shearing and bending stresses. These strata, when freed on one or more sides through the process of tunneling, or when disturbed by blasting, aim, so to speak, to resume their original or normal position; thus the bulging of tunnel floors, crushing of side walls, shelling of the rock and even twisting or revolving of the whole bore around a horizontal axis. Such phenomena have occurred either during the construction of a tunnel, or only after a period of several months or years, as for instance in the Simplon, Bosruck, Karawanken, Weissenstein and Ricken tunnels.

In order to resist safely and permanently the stresses brought upon the tunnel lining by movements or disturbances of the strata, it becomes necessary to locate a bore at such a depth that it will not be affected by abnormal ground pressure, or else give the bore a shape or cross section, and the lining such strength as will best take care of the stresses borne by the same.

In a deeply overlaid tunnel, the rock temperature may become excessive also, and formerly, when artificial means of ventilation and refrigeration were still in a crude stage, much stress was laid on the possible depth below the surface of the ground a bore could be successfully driven.

Among other factors entering into consideration, underground springs play a very important part, for the head or pressure acting at their outlet or, in the particular case, at tunnel elevation, may be high, and thus become a serious hindrance to progress, as experienced in the Simplon, Loetschberg, Granges, Bosruck and Mont d'Or tunnels.

Usually, the area drained by a long tunnel is large, and the amount of water often takes the proportion of a river, as for instance in the Simplon tunnel, 44 sec. ft.; Bosruck, 78 sec. ft.; Granges, 30 sec. ft.; Mont d'Or, 100 sec. ft.

In addition to considerations governing the traffic and capacity of a tunnel, the size and number of bores are largely governed by geological considerations. The uncontestable advantages gained in driving the Simplon tunnel by means of twin bores

has brought into use a tunneling method which, undoubtedly, will find further application; for, in deep tunnels subjected to enormous ground pressure, it is doubtful whether economy can be realized by constructing a double-track bore whose masonry lining will resist safely pressures similar or superior to those met with in driving the Simplon tunnel. (Maximum thickness of tunnel arch and invert, 66 and 98 in., respectively.) In case of twin bores, consisting either of two single-track tunnels, or of a double-track bore with auxiliary heading or gallery, the proper distance between bores is a question whose successful solution is yet to be found.

It is generally admitted by geologists and engineers connected most intimately with the driving of the Simplon tunnel, that the distance of 56 ft. center to center of bores of this tunnel is too small, especially in pressure zones, and that it should be preferably 2 or 3 times the above figures; for already, during construction and during the following 6 or 8 years, serious disturbances took place in various sections of the parallel and transverse galleries, even in the sections which had been lined ultimately. It is the prevailing opinion of geologists and engineers that the auxiliary bore or heading, driven for construction or ventilating purposes, in connection with a tunnel system, should be lined at the very outset, at least in pressure zones, to avoid deformation or settlement of the strata, which result in throwing additional and unsymmetrical loads on the main bore.

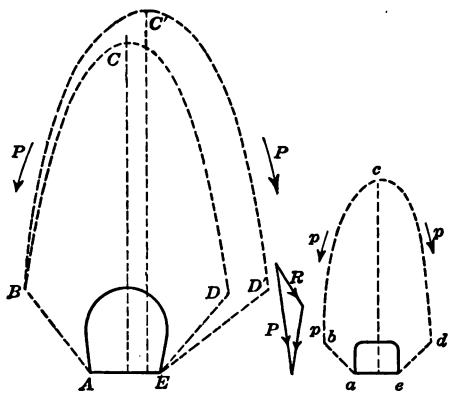


FIG. 2.—Diagram illustrating distribution of ground pressure in twin tunnels.

Fig. 2 illustrates a double-track tunnel together with an auxiliary bore, located say 60 ft. from the main bore. The weight acting on the main bore is represented by *A-B-C-D-E*, on the assumption that the side walls of the tunnel are unable to resist crushing. The weight acting in a similar manner on the small bore is represented by *a-b-c-d-e*. Thus, the material between, or

separating the bores, is subjected to unsymmetrical loads, in a manner somewhat similar to that of a bridge pier receiving the thrust of unsymmetrical arch spans. The resultant R of the thrusts P and p acts toward the small bore and, should the latter be unable to resist this additional load, deformation will take place, and, through displacement of the strata, the weight of the material acting on the main bore may assume the shape indicated by the dotted lines A-B-C'-E, and thus cause unsymmetrical stresses in the masonry lining of the main bore. According to the material penetrated, or the inclination and cohesion of the strata, more or less favorable conditions of equilibrium will take place.

The transverse galleries connecting the main bore with the auxiliary bore or heading are far from adding to the strength of the barrier dividing these; for construction reasons, these galleries are not driven at right angle to the main bore, but at a smaller angle (Simplon tunnel, 50° about), thus weakening materially the material receiving the thrust of the two bores.

Driving Methods as Affected by Geological Considerations

These are largely governed by conditions of economy, the geological formation of the range penetrated by the bore being directly responsible for certain features only. The top and bottom heading method has been adopted in driving practically all railroad tunnels 3 miles long and over, during the past decade, and the results obtained have fully warranted this method, in practically every kind of rock formation.

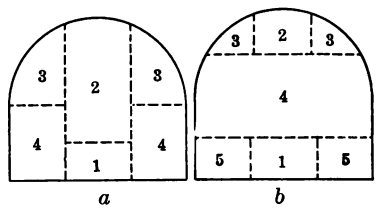


FIG. 3.—Sketch illustrating method of excavating long tunnels.

The top and bottom heading method has been somewhat modified to meet different conditions of stratification and cohesion of the ground penetrated; in rock subjected to enormous pressure, it has been found necessary to drive top and bottom headings of small cross section (Fig. 3*a*) in order to avoid setting in motion large masses of overlaying material, bracing these strongly as work proceeds, keeping the lining close to the heading.

In materials less subjected to pressure, the center cut method (Fig. 3*b*) has become decidedly much in favor, being far less costly than the former method.

The improvement made in tunneling machinery has also greatly simplified mining operations, and the drilling of bore holes is now done practically regardless of the dip and strike of the strata. The motto: "Break the rock without disturbing the adjacent strata" has done away with deep bore holes of small diameter, loaded with low strength explosives, thereby avoiding overbreaks, shattered roofs, and the necessity of keeping the timbering close to the heading's face.

Experience has taught that, all things being equal, with a well trained mining crew, high driving progress could be obtained in soft and hard rocks, at a variable expense of explosives and bore holes.

The Timbering and Lining of Tunnels as Affected by Geological Considerations

The necessity of timbering, pending the construction of the lining, depends to a large extent on the skill displayed in excavating a bore. The practice now followed in connection with the driving of long and deeply overlaid tunnels consists in carrying out all operations as speedily as practicable, making the lining follow closely to the excavation. Besides reasons of a purely economical nature, the aim of this method of procedure is many-fold: In materials weathering rapidly upon exposure to the action of air and water, it is advisable to line a bore without delay, in order to avoid swelling of the ground and thus avoiding also heavy timbering and additional excavation or trimming. This is true chiefly in shaly materials, clays, marls, chalks, soft sandstone, etc. In general, wet tunnels require timbering and a permanent lining, except possibly bores driven through granitoid rocks, gneiss, and, generally speaking, rocks of ancient formation.

According to features common to the geological formation of mountain ranges pierced by tunnels, these can be classified into three orders: 1. Tunnels driven through igneous and metamorphic rocks, as for instance the Cascade, Stampede, St. Paul Pass, Mont Cenis, St. Gothard, Arlberg, Albula and Rogers Pass tunnels. 2. Tunnels driven through aqueous rocks, as the

Scranton, Kingwood, Mont d'Or, Granges, Weissenstein, Hauenstein, Bosruck, Karawanken and Ricken tunnels. 3. Tunnels driven through alternate strata of igneous, metamorphic and aqueous rocks, as the Simplon and Loetschberg tunnels.

Class I. Materials Penetrated: Granitoid Rocks, Gneiss, Schists, Etc.

Characteristic Features.—Absence of abnormal rock pressure, usually, and little water encountered. In deeply overlaid tunnels the low conductivity of rocks gives rise to high rock temperature.

Tunnels pertaining to this class are driven usually without extraordinary difficulties; timbering is used chiefly to avoid falls of rocks loosened by blasting. Long sections of tunnel can be driven without timbering at all. A drainage canal of moderate dimension only is required, and unless tunneling under large bodies of water such as a river or a lake, the driving progress is not likely to be hampered by unusual inrush of water. Recent practice favors lining long tunnels, but the lining of bores under this class will have a minimum thickness; the side walls can be made straight and no invert will be required. In deeply overlaid tunnels, the rock temperature may be high, thus necessitating a powerful ventilating and refrigerating plant. The chief features governing the driving progress will be the hardness or toughness and the temperature of the rock penetrated.

Class II. Materials Penetrated: Limestone, Shales, Clays, Marls, Conglomerates, Sandstones, Breccias, Gypsum, Etc.

Characteristic Features.—Ground pressure and water to contend with usually. High heat conductivity of rock due to humidity, hence low rock temperature. Possibility of encountering gases due to carboniferous deposits.

The materials penetrated by tunnels pertaining to this class may vary greatly in hardness and cohesion, and stratification plays an important part also. Alternate water-bearing strata of soft and hard rocks are to be anticipated. Rock of similar formation may be dry if unstratified, and very wet if stratified more or less vertically. In limestone formation, large pockets of water are liable to be encountered, and thus become a serious hindrance to progress. Gases can be expected in sandstone, limestone and conglomerate formations.

The pressure of the ground may require heavy timbering, to resist crushing of the roof, squeezing of the sides and uplifting of the floor. In many instances, a masonry lining will be required to resist ground pressure throughout the periphery of the bore. The drilling operations may be subjected to considerable variation, and often it becomes necessary to take adequate precautions when blasting, so as to enable the mining crews to be out of reach of a blow-out.

Class III. Materials Penetrated may be Alternate Sheets or Strata of Igneous, Metamorphic and Aqueous Rocks

Characteristic Features.—Great variation and uncertainty as to rock pressure, ground temperature and water to contend with, all depending on the stratification, whether horizontal or vertical, or very folded and contorted.

The contingencies pertaining to the driving of tunnels under this classification are a combination of those to be expected when driving tunnels of the first and second class. Unusual complications may result from the complexity of the stratification, especially at the contact zones of two different kinds of materials, and the driving progress may vary suddenly from good to bad or vice versa.

CHAPTER II

HEADINGS AND TUNNELS OF SMALL CROSS SECTION DRIVING METHODS

Headings, as driven in connection with tunnels of large cross section, such as railroad tunnels, or tunnels of small cross-sectional area driven in connection with mining work, water supply and irrigation systems and water-power developments, represent, by far, the largest percentage of bores driven, in general.

When speed in driving is a matter of first consideration, the bore is driven 6 or 7 ft. high, and a trimming or stoping crew follows the heading crew, at some distance back of the face and excavates the roof of the bore, to the height or shape desired; or a bench of 3 or 4 ft. high is left, and same is excavated when 10 or 20 ft. back of the heading's face. In order to simplify the setting up of drills, a heading or tunnel of small cross section should preferably be not over 8 ft. high and 12 ft. wide.

When designing water-conveying tunnels, the section of the bore is determined usually by taking into consideration the section most favorable to the carrying capacity, that is, a circular section; as driving of circular tunnels is more costly than that of tunnels with straight or slightly battered sides, circular tunnels should be avoided whenever possible.

The attention of the designer is here called to the fact that, in many instances, it will be found more economical to increase the area of the tunnel by adding a foot or two to its width, thus keeping the roof of the bore to such height as will enable the bore to be driven in one operation.

Headings of Railroad Tunnels, and of Tunnels of Small Cross Section

For the purpose of increasing speed in driving, and in order to decrease the cost of haulage, the points of attack can be multiplied in certain instances, by sinking shafts from the ground surface down to tunnel grade, or by driving adits, perpendicularly, or nearly so, to the bore in a horizontal plane. The choice between a shaft and an adit depends largely on the topography of the site considered, but, all things being equal,

it will be found more economical to drive an adit, even if its length should be 2 to 3 times the depth of a shaft.

The following tables give the dimensions of various headings and tunnels of small cross section:

Name	Width, ft.	Height, ft.	Area, sq. ft.
Loetschberg	10	6.5	65
Simplon	10	6.0	60
Granges	11	7.0	77
Mount Royal	12	8.0	96
Ricken	10	6.5	65
Hunters Brook	15	9.0	135
Arthur Pass	10	8.0	80
Turchino	9	9.0	81
Karawanken	10	8.0	80
Mine and Mine Drainage Tunnels			
Oneida	9.0	7	63
Lausanne	12.0	8	96
Lucania	8.0	8	64
Marshall Russell	8.0	9	72
Newhouse	8.0	8	64
Rawley	8.0	7	56
Roosevelt	10.0	6	60
Stilwell	7.0	7	49
Water Supply, Power and Irrigation Tunnels			
Buffalo	8.0	15.0	120.0
Joker	11.0	12.0	132.0
Laramie Poudre	7.5	9.5	71.0
Gunnison	10.5	12.2	128.5
Strawberry	9.0	10.5	76.0
Strikler	4.0	7.0	28.0

In bores which are not to be provided with a lining, or when the material excavated is not suitable for lining purposes, it will often be found cheaper to dispose of it through adits, and in wet tunnels, adits will also do away with pumping.

According to the purpose they are called to serve, adits are driven either toward or from the main bore. When they serve the purpose to decrease the cost, or to facilitate the operations

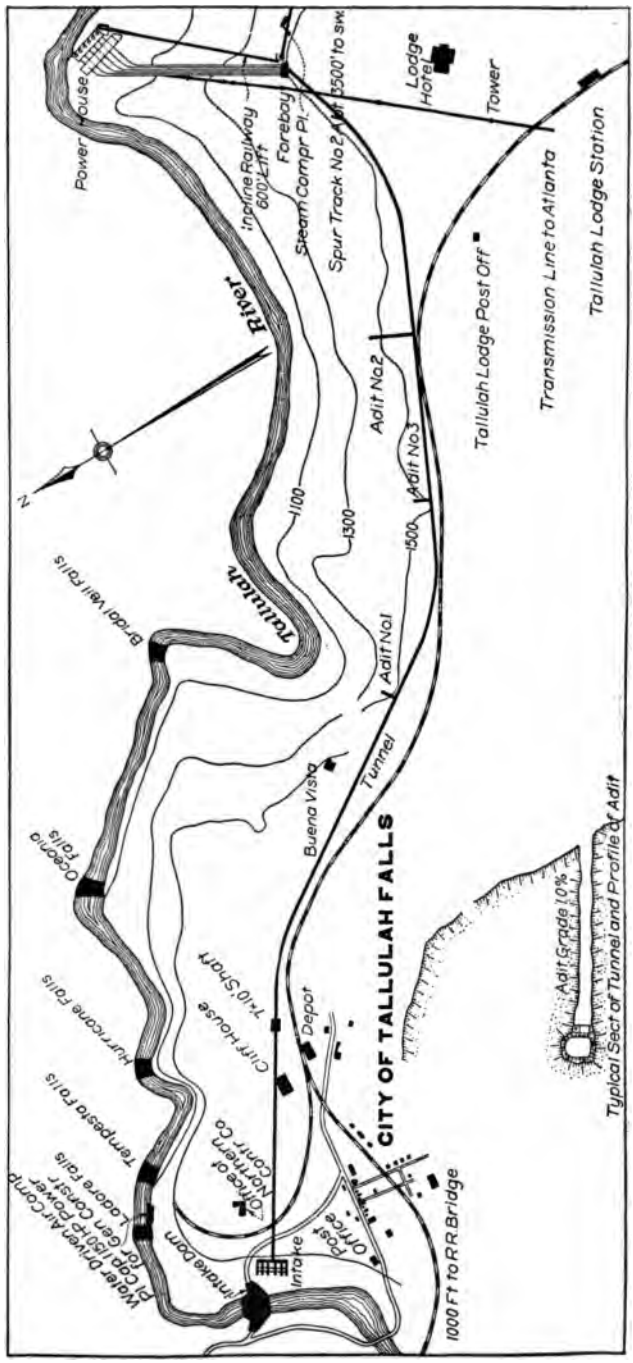


FIG. 4.—Plan of Tallulah Falls development showing tunnel route.

of haulage, adits are driven from the bore toward the surface, but when they serve the purpose of increasing the points of attack, they are driven from the surface toward the main bore. Sometimes, a combination of adits and shafts is used, as was done in connection with the Tallulah Falls tunnel, Fig. 4.

DRILLING METHODS

The opinion of tunnel men, as far as drilling is concerned, in connection with headings or bores of small cross section, varies greatly. In this country, the method of using a large number of deep bore holes, loaded with a relatively small amount of explosives, has been generally favored, although during the past 4 or 5 years a change in method toward using shorter bore holes has taken place gradually.

In Europe, the method of using shallow holes of large diameter, loaded with a relatively large amount of powder, is used very extensively.

The divergence between these methods is, to some extent, due to the difference in labor available on both continents, and also to the purpose of, and the material penetrated by, the headings or bores under consideration.

In adits, mine and water-conveying tunnels, the chief aim is, all things being equal, to carry on work at a minimum cost, keeping the excavation as closely as possible to certain specified lines and grades, thereby reducing the amount of excavation and, in certain instances too, of the concrete or masonry lining.

When driving headings of long tunnels, altogether conditions prevail and economy can be expressed only in terms of the enlargement and lining work, the cost of which depend to a large extent on the progress made in the heading, and this accounts for giving first consideration to speed in driving. This is obvious, for the type of timbering to be used in the enlargement work, the cross section of the bore, also the type of lining to be adopted, and which must be designed in advance, depend on the success in driving the heading. To this end, the heading is driven practically regardless of shape or cross section, a minimum rather than a maximum section being specified for reasons of construction. No special attempt is made to obtain an even floor, as the drainage canal is excavated later on, and the alignment of the heading in a horizontal plane is also

of secondary importance. On the other hand, care is exercised not to shatter the overlaying strata, especially in folded mountains, the rock of which is often subjected to latent stresses. In certain cases this feature alone warrants the use of shallow holes for blasting purposes.

Number of Bore Holes

The number of bore holes drilled in a heading or tunnel face vary according to the size of the bore and the hardness, toughness and stratification of the rock penetrated; therefore no strict rule can be laid down to guide the tunnel driver. Yet, a glance at Tables A, B and C, below, shows that, in general, the size of the bore is a governing factor, more holes being required per sq. ft. of face for a small bore than for a large one. There seems to be also a slight difference between the number of square feet area of heading's face per hole, for bores driven through igneous and through sedimentary rocks. The depth of bore holes seems to affect also their number, as will be found when comparing Tables A and B with Table C. The bore holes in the first two tables are chiefly deep holes, that is, holes 6 to 12 ft. deep, while those in Table C are not over 5 ft. deep. For instance, for igneous rocks, the average number of square feet of heading area per bore hole is 3.1, according to Table A, as against 4.85 sq. ft. as per Table C. From Table B it will be found that, for igneous rocks and an average heading area of 107.5 sq. ft.,

TABLE A[1]

Area of heading, sq. ft.	No. of bore holes	Materials penetrated	Sq. ft. of heading per bore hole
57	15–19	.....	3.3
60	24	Granite	2.5
70	21–26	Granite	3.0
65	25	Granite	2.6
72	18–20	Granite-Gneiss	3.8
65	19	Gneiss	3.4
60	24–26	Granite	2.4
65	16	Diabase	4.0
50	16–18	Limestone	2.9
50	18	Limestone, sandstone	2.8
Average for	igneous rocks	.....	3.1 sq. ft.

[1] Taken chiefly from Bulletin 57, Bureau of Mines.

TABLE B

Area of heading, sq. ft.	No. of bore holes	Materials penetrated	Sq. ft. of heading per bore hole
120	22	Limestone	5.5
120	22	Limestone	5.5
120	24	Shale	5.0
120	24	Sandstone, shale	5.0
120	21	Gneiss	5.7
145	25	Granite	5.8
90	15	Granite	6.0
90	20	Granite	4.5
95	18	Rhyolite	5.2
110	22	Sedimentary rocks	5.0
Average for	igneous rocks		5.4
Average for	sedimentary rocks		5.2

TABLE C

Materials penetrated	Area of heading	No. of bore holes	Sq. ft. of heading area per bore hole	Depth of hole	Progress per attack	Efficiency Col. 5 / Col. 4	Dynamite consumption per cu. yd.	Bor hole per cu. yd.
	1	2	3	4	5	6	7	8
	Sq. ft.			Ft.	Ft.	Per cent.	Lb.	Ft.
Limestone	71.0	14.2	5.0	5.0	4.8	96	5.0	5.6
Crystal schist	67.0	13.7	4.9	4.2	3.4	81	8.2	6.9
Quartz porphyry	67.2	12.7	5.2	4.3	3.7	85	7.3	6.1
Limestone	67.0	14.5	4.6	5.0	4.8	96	5.6	6.1
Granite	66.5	14.0	4.7	4.4	3.9	90	7.1	6.4
Granite	67.5	15.0	4.5	4.5	4.1	90	6.9	6.7

the number of square feet of heading area is 5.4 as against 3.1 in Table A, for headings averaging 65 sq. ft. area. But, from Table C, it is found that, for headings of slightly different cross section, driven through various materials, the number of bore holes can be kept constant by varying the consumption of explosives, according to the hardness and toughness of the rock.

The following tables giving the consumption of explosives, progress, etc., for stratified and unstratified materials, of various kinds, will be found of interest:

	Brandleite tunnel	Albula tunnel
Kind of rock penetrated	Felsite porphyry	Granite
Stratification	Unstratified	Stratific. steeply incl.
Overlaying depth, ft.	1300	2600–3000
Progress per 24 hr.	13.2	21.6
Consumption of drill steel per lin. ft. of bore hole.	.....	0.95
Explosive consumption per lin. ft. of heading, lb.	19.2	13.9
Progress per attack	3.78	4.28
Number of drills in operation	3.0	3.0

SIMPLON TUNNEL

Kind of rock, stratification	South side			North side	
	Gneiss, horizontal	Gypsum, slightly inclined	Gneiss, slightly inclined	Limestone, slightly inclined	Hornblende gneiss, steeply inclined
Overlaying depth, ft.	2300–4900	5300	5600	5600	5200–7200
Progress per 24 hr., ft.	14.2	24.8	17.4	18.2	21.8
Number of drill steel per lin. ft. of bore hole.	1.67	0.67	1.27	1.4	1.25
Explosive consumption per lin. ft. of heading, lb.	17.3	18.4	22.1	20.0	15.2
Progress per attack, ft.	3.79	3.98	3.13	3.62	4.15
Number of drills in operation.	4.0	4.0	4.0	4.0	4.0

Location and Direction of Bore Holes

Although no method of locating bore holes has yet been standardized, there exist nevertheless two methods which are

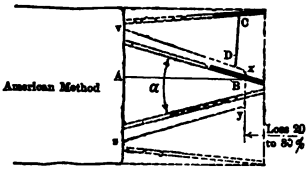


FIG. 5.

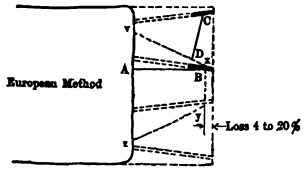


FIG. 6.

FIGS. 5 and 6.—Method of drilling bore holes in headings or tunnels of small cross section.

used most extensively: the center or V-cut method, used chiefly in this country, Fig. 5, with relatively long bore holes, and the

straight-cut method, used in Europe, Fig. 6, in connection with shallow holes. Both methods are used in somewhat modified forms, according to the kind and stratification of the rock penetrated, and also the method of mounting the drills.

The center-cut method, as used in connection with drills mounted on a horizontal bar, is illustrated by Figs. 7 and 10 and by Fig. 8 with drills mounted on a vertical column.

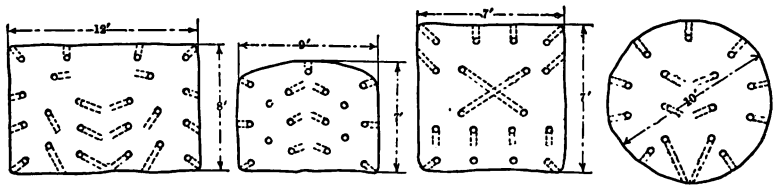


FIG. 7. Mount Royal tunnel. FIG. 8. Oneida tunnel. FIG. 9. Yak tunnel. FIG. 10. St. Louis waterworks tunnel.

FIGS. 7–10.—Diagrams illustrating method of drilling bore holes.

A modified type of the center cut is illustrated by Fig. 9; here the cut holes are sloped both in a vertical and horizontal plan and, on this account, the cut is also named "pyramidal cut."

The location and direction of bore holes is also influenced by the dip and strike of the strata, that is, in well-stratified rock, and when using deep holes especially, some advantage is gained by firing certain holes first. For instance, in Fig. 11 the charge nearest to the roof would be fired first, while in Fig. 12 that nearest to the floor.

In European headings, the holes are drilled nearly straight, as shown by Figs. 6 and 13. The reason for following this method lies in the fact that the drills, mounted on a horizontal bar, in a narrow heading, are allowed little play in a horizontal plan; besides, it takes much time to locate deep holes, so as to make their bottom end intersect, and when the heading's face is rough, much preliminary work is required to start a hole at a specified point, especially with piston drills, thus robbing valuable time which, otherwise, could be used for drilling.

It happens very often that, excepting in shaly materials, soft sandstone or limestone, the material within the line *v-x-y-z*, Fig. 5, and especially that nearest to the face, between *v-z*, instead of being shattered in small fragments, is forced out in large pieces, a feature very objectionable to mucking. In

Fig. 6 the line of least resistance *A-B* coincides very nearly with the bore hole and, in this respect, the line of least resistance *A-B*, Fig. 5, is shorter than the bore hole, but, on the other hand, the larger the angle α the longer the line of least resistance *C-D* of the side holes will be, thereby causing the materials removed by the side holes to break into large pieces and to be thrown against the sides of the heading, instead of being thrown forward. Thus, the muck pile will accumulate directly in front of the heading's face, as shown by Fig. 14, instead of piling as shown by Fig. 15.

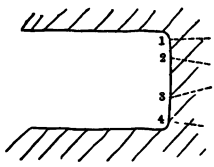


FIG. 11.

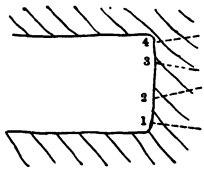


FIG. 12.

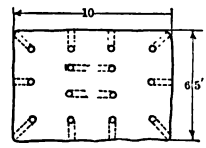


FIG. 13.

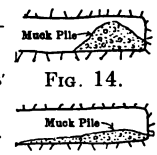


FIG. 14.

FIG. 15.

FIGS. 11 and 12.—Diagrams showing order of firing rounds according to dip or strike of the strata.

FIG. 13.—Drilling diagram—European headings.

FIGS. 14 and 15.—Muck pile formation due to different method of blasting in headings.

Depth of Bore Holes

There is a wide divergence with reference to the depth of bore holes adopted in tunnel work in this country; for instance, bore holes 8 to 10 ft. deep are used both in headings 8 or 16 ft. wide, in soft or hard rocks. On the other hand, shallow holes 4 to 5 ft. deep have been adopted in European headings driven through almost any kind of rock. An analysis of both methods seems to indicate that the efficiency of bore holes, that is, the ratio $\frac{\text{Progress per attack}}{\text{Length of bore hole}}$, is decidedly in favor of shallow holes.

In column 6 of Table C, page 14, the efficiency of shallow holes runs from 81 to 96 per cent., whereas, by using deep holes, the efficiency hardly averages 70 to 75 per cent., in hard and tough materials. This divergence is due to the fact that the bottom end of deep bore holes has a small diameter usually, and thus the charge of explosive is spread over a relatively great distance, whereas, by using shallow holes of large diameter, the charge of explosive is concentrated at the bottom of the bore hole.

Two disadvantages are incurred by the use of shallow bore holes: The consumption of explosives is larger by 1 to 3 lb. per cu. yd. of rock excavated, according to its hardness and toughness, and the organization of the mining operations must be better, in order to obtain the same rate of progress, as it becomes necessary to drill and fire approximately twice as many rounds. However, the increase in efficiency of bore holes usually compensates for the surplus of explosives required (especially where wages are high), as the saving effected affects both labor and power charges.

Furthermore, less time is required to drill shallow holes, as the steel bits are changed more rapidly, and less trouble is experienced due to bits "sticking," especially when using piston drills.

Another advantage made possible by the use of shallow bore holes lies in the possibility of using hammer air hand drills, that is, a one-man drill requiring no setting up, practically, and which can be used effectively in soft rocks such as limestone, sandstone, shale, molasse, etc. In the Hauenstein tunnel three such drills enabled monthly driving progress of 750 ft. to be made in a heading of 78 sq. ft. area.

The length of bore hole per cu. yd. is not increased by the use of shallow holes, as will be found when comparing column 8 of Table C, page 14, with the following table, the amount of bore hole per cu. yd. being 6.45 and 6.3 ft. for deep and shallow holes respectively.

Name of tunnel	Material penetrated	Length of bore hole per cu. yd.
Gallitsin	Shale	7.0 ft.
Sutro	Trachyte	8.7
Musconetcong	Gneiss	6.0
Melones Mines	Diabase	7.6
Hogsback	Diabase	5.0
Walkill	Shale	5.8
Tequiquac	Sandstone	5.0
Average		6.45 ft.

The following table gives the length of bore holes used in various tunnels of small and medium cross section:

Name of tunnel	Width, ft.	Height, ft.	Depth of cut holes, ft.	Depth of side holes, ft.	Kind of material
Mount Royal	12.0	8	8	6.5	Limestone
Lausanne	12.0	8	7.5–8	7–8	Shale
Buffalo	15.0	8	8	7.0	Limestone
Oneida	9.0	7	8	7.0	Conglomerate
Strawberry	10.0	8	7	6.0	Limestone and sandstone
Walkill	14.0	8	11–12	10.0	Shale
Nisqually	9.5	11	8	6–7	Rhyolite
Moodna	14.0	8	10	8–9	Sandstone and shale
Lucania	8.0	8	9	8.0	Granite
Roosevelt	10.0	6	7	6.0	Granite

Method of Firing

In the western part of the United States and in Europe, safety fuses are used almost exclusively, while in the central and eastern parts of this country, electric detonators are used to a very large extent.

Detonators or blasting caps are sold commercially according to the weight of the mercury fulminate they contain. The grades as used in connection with safety fuses are known as $3X$, $4X$, etc., $8X$ being the maximum; while that of electric detonators are known as single strength, double strength, etc., quadruple strength being the maximum grade.

When used in connection with gelatine dynamite, the $5X$ or $6X$ grade, or the double-strength electric detonators, should be used so as to insure complete and instantaneous combustion and detonation, thereby reducing the amount of carbon dioxide resulting from incomplete combustion.

When used in connection with shallow bore holes, the explosives, after having been inserted into the bore holes, should be carefully tamped, so as to increase the efficiency of the round. With deep holes, tamping is of lesser importance and is omitted almost entirely in many instances. The tamping usually consists of clay or a mixture of clay and sand, wrapped in paper bags, prepared in advance.

In general, the cut holes are fired first, then the lifters and finally the side holes. When using deep holes, firing depends

sometimes on the stratification of the rock, but with shallow holes, the center holes are fired first.

In European headings, a uniform strength of explosives is used generally in one heading, but the center or cut holes are loaded with a heavier charge of explosive than the side holes. The fuses are usually cut all to the same length, those pertaining to the cut holes being ignited first.

In this country it is the practice, in many instances, to fire the center cut first, then the lifters and finally the side holes, thus requiring two or three operations. When using electric detonators, this inconvenience is obviated by using delay-action detonators, which permit all holes to be fired at distance in two or three rounds.

Electric detonators are used in connection with a portable battery or with the current used in connection with the lighting system, if any.

Blasting and Consumption of Explosives

Gun powder, made of niter, sulphur and charcoal, is hardly used any more in tunnel work, modern explosives such as gelatine and ammonia dynamites being used instead, almost exclusively. The last-named explosives are made and sold commercially at prices varying according to their strength. Gelatine dynamite is made in strength varying from 30 to 70 per cent. and ammonia dynamite in strength of 30 to 60 per cent.

These two explosives possess the advantage of being handled more safely than straight nitroglycerine dynamite and generate about 20 to 25 per cent. less carbon monoxide, but, on the other hand, they generate from 15 to 20 per cent. more carbon dioxide.

The strength used in heading work varies according to the character of the material penetrated, a higher grade being used for tough and hard rocks than for softer or more brittle ones.

On the Los Angeles aqueduct, 40 per cent. gelatine dynamite was used, also some 70 and 75 per cent. strength, as well as some 40 per cent. ammonia dynamite. On the Catskill aqueduct, chiefly 60 per cent. gelatine dynamite was consumed. At the Hunters Brook tunnel 60 per cent. forcite was used. In the Simplon tunnel, dynamite with 83 per cent. nitroglycerine was used on the south side and gelatine with 64 per cent. nitrogly-

cerine and 24 per cent. soda nitrate on the north side. At the Mont d'Or tunnel, 93 per cent. gelatine dynamite was used.

In many instances, a higher strength explosive is used in the cut holes and a lower grade in the side holes and lifters. The following table gives the consumption of explosives used in driving American and European tunnels, driven through various kinds of materials:

EXPLOSIVE CONSUMPTION IN AMERICAN HEADINGS

Name of tunnel	Material penetrated	Lb. per cu. yd.
Gallitsin	Shale	6.5
Croton aqueduct, old	Gneiss	4.0
Sutro	Trachyte	3.3
Musconetcong	Gneiss	4.4
Tequiquac	Sandstone	4.5
Mount Hood	Shale	2.4
Rondout	Limestone, grit	4.5
Buffalo	Limestone	3.0
Walkill	Shale	4.3
Laramie Poudre	Granite	4–4.9
Hunters Brook	Gneiss	7.5
St. Paul Pass	Quartzite	7.0

EXPLOSIVE CONSUMPTION IN EUROPEAN TUNNELS

Name of tunnel	Material penetrated	Lb. per cu. yd.
Kandergrund	Limestone	4.2
Loetschberg	Limestone	5.0
Loetschberg	Crystalline schist	8.2
Loetschberg	Quartz porphyry	7.3
Loetschberg	Granite	7.1
Kubel	Shale	3.5
Simplon	Gneiss	7.8
Simplon	Hornblende gneiss	6.8
Löntsch	Limestone	5.2
Granges	Marl, molasse	2.0
Granges	Limestone, white	5.3
Granges	Limestone, brown	5.2

CHAPTER III

HAULAGE METHODS

Excepting mules or horses, which have been used in connection with driving a few relatively long tunnels of small cross section, electric and gasoline locomotives have been adopted to a large extent during the past 10 years.

In the Lausanne drainage tunnel, electric locomotives, with trolley system, hauled cars of about 80 cu. ft. capacity. In the Walkill pressure tunnel of the Catskill aqueduct, 11-H.P. electric locomotives consumed 0.67 kw.-hr. per cu. yd. of rock, per 1000 ft. lead in the tunnel. In the pressure tunnel of the same system, under the city of New York, both trolley and storage battery electric locomotives were used, each of these types being shown in Figs. 15*a* and 15*b*. In the Strawberry tunnel, the muck was hauled by an electric locomotive, in steel cars having a capacity of 47 cu. ft. These cars, especially designed for that work, were constructed of steel throughout, and they required very little attention. The locomotive handled anywhere from eight to twelve cars on a train, at a speed of 4 to 6 miles per hr. One motorman and a brakeman hauled and dumped the muck for one shift. The muck cars were constructed in such a way that they could be dumped by being lifted by a 7-½-ton derrick, actuated by a 40-H.P., D.C. motor. The derrick was moved once in a month, no other work being required on the dump, except to clean out the cars.

The track was laid with 25-lb. rail, and gauge being 24 in. The traction current was 250 volts, and the 0000 grooved wire supplying the current was strung on pine poles, spaced 40 ft. center to center, Fig. 16, and fastened to the ties.

In the Gunnison tunnel, tramming was carried on by electric locomotives of 6 tons weight each, with a guaranteed drawbar pull of 2400 lb. Their speed was 6 to 8 miles per hr.; the gauge of the track was 24 in. In the western end of the tunnel, a side dump car having a capacity of 35 cu. ft. was used. In the eastern end of the bore, a non-dumping car mounted on four wheels

FIG. 15*a*.—Electric locomotive with trolley.

FIG. 15*b*.—Storage battery locomotive used in Brooklyn section of aqueduct tunnel.

(Facing page 22.)

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX
TILDEN FOUNDATIONS

rigidly attached to the car body was used. This car had a capacity of 54 cu. ft. It was so constructed that it could be lifted by a derrick and the entire car turned upside down, to dump the contents; dumping was done by the tramming crews. In the beginning of the work, the hoist and swinging device on the dump derrick, at the east portal, was operated by compressed air motors. These motors gave trouble due to freezing in cold weather, and they were subsequently replaced by electric motors.

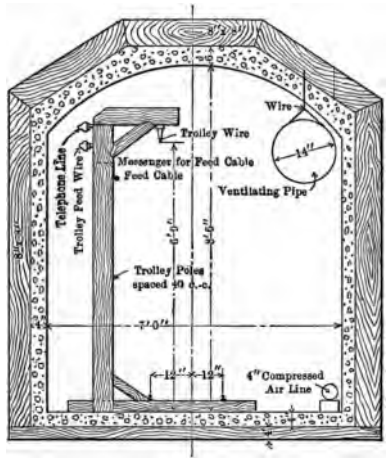


FIG. 16.—Cross section of Strawberry tunnel.

In the bottom heading of the Mount Royal tunnel, there were about 175 tunnel cars for hauling out the muck; they were built especially strong to withstand the strain due to the rock falling into them from above, a condition imposed by the bottom heading method of tunnel driving that was used.

There were six small storage battery locomotives; these were originally operated by gasoline. The storage battery was carried on a trail car, there being two batteries for each locomotive. When using the gasoline locomotives, it was hoped that the carbon monoxide could be changed to dioxide by passing over lime, but this was only partly successful. The fumes finally became so objectionable that 110-volt electric locomotives were substituted for the engines. Later on, when more room became available, a trolley pole and another 110-volt motor were added, the two motors operating in series, being supplied with 220-volt power from the trolley wire.

The following table gives the cost of storage battery haulage as compared with horse haulage, in a tunnel near Idaho Springs. The cost includes also the cost of current for two arc lights and for twelve incandescent lamps. The cost of superintendence and of discount to patrons is not included. The cost of material and repairs for the locomotive is excessive, owing to the fact that much difficulty was experienced with the carbon lights used, moisture in the tunnel making frequent short circuits and burning out

lamps and sockets. The costs for April and May would be an average. Probably a fairer comparison of relative costs would be the figures for July, September and October for horses, and for December, January and February with the locomotives, making an arbitrary figure of $15 per month for repairs and material, including the sand used.

COST OF HORSE HAULAGE

Month	Labor	Teams	Total	Ton-miles	Cents per ton-mile
May	$172.00	$96.08	$268.08	2,147	12.5
June	222.45	136.87	359.32	3,515	10.2
July	291.20	199.60	490.80	4,290	11.4
August	399.75	213.48	613.23	5,901	10.4
September	299.10	181.45	480.55	4,621	10.4
October	326.95	143.80	470.75	4,921	9.6
Totals	$1,711.45	$971.28	$2,682.73	25,395	10.6

COST OF STORAGE BATTERY LOCOMOTIVE HAULAGE

Month	Labor	Material	Repair	Power	Total	Ton-miles	Cents per ton-mile
December	$200.50	$27.56	$6.62	$56.21	$290.89	4,452	6.5
January	192.25	41.36	12.78	55.60	301.99	4,491	6.7
February	259.75	21.40	10.96	58.30	350.41	4,832	7.3
March	190.00	10.15	.....	48.90	249.05	2,072	12.0
April	143.84	4.36	6.14	44.50	198.84	1,632	12.2
May	11.67	8.50	1.75	42.20	164.12	1,435	11.4
Totals	$1,098.01	$113.33	$38.25	$305.71	$1,555.30	18,914	8.2

Ventilation of Tunnels of Small Cross Section

Mostly blowers, capable of exhausting and forcing in air at a relatively high pressure, are used, although fans of the centrifugal type are used to some extent too.

In the Walkill tunnel, electric-driven blowers of 7500 cu. ft. capacity per min. were forcing in air at 6.5 oz. pressure, through 12-in. diameter galvanized iron pipes.

In the Strawberry tunnel, electric-driven blowers of 3000 cu. ft. capacity, driven by a 40-H.P. motor, forced in air through 14-in. pipes, the aim being to keep not more than 15 parts of CO_2 in 10,000. The temperature of the air was about 63° F. From tests, it was found that air contained from 6 to 10 parts of CO_2

in 10,000. After a blast, the blower was run at full speed from 10 to 20 min. to clear the gas and smoke, after which it was cut down to three-fourths speed for the remainder of the shift. Immediately after shooting, a jet from the compressed air line was turned into the heading, at the face, to drive the smoke back to the mouth of the ventilating pipe, which was carried from 60 to 100 ft. back, to prevent too much flying rock from striking it.

The ventilating pipe was manufactured at the tunnel from sheets of steel that made 4 ft. length. The pipe was made in 16-ft. length and tarred before being put up to prevent rust and to seal the seams and joints. The ventilating pipe was suspended along the top of the heading, Fig. 16, by iron straps spaced 16 ft. center to center nailed to the timbering. The 16-ft. joints of pipe were driven together solidly on being put in the tunnel and the joints were wrapped with canvas or burlap, dipped in hot coal tar, to strengthen and seal the joint.

In the Gunnison tunnel, ventilation was carried by means of cycloidal blowers. In the eastern end of the bore, one blower was located in the power house and was direct connected to a 25-H.P. steam engine. This blower was used as an exhaust fan, and was operated for two or more hours after blasting to draw foul air from the heading. As the heading advanced, the suction draft was carried as close to the heading as possible by 16-in. slip-joint riveted iron pipes. This pipe was shipped to the work in sheets, rolled, punched and nested, and afterward riveted up as required on the work. After the heading had advanced about 6000 ft. it became necessary to install another blower in the pipe line to act as a booster. This second blower was operated by an electric motor. In the eastern heading little trouble on account of ventilation was encountered, as the progress was entirely in granitic rock, with a temperature of about 65° F. and entirely free from obnoxious gases.

In the western heading conditions were so severe that radical treatment of the problem was required from the outset. In driving heading No. 2, eastward from the main shaft, small pockets of explosive gas were encountered within 100 ft. of the shaft. In order to preclude any possibility of an accumulation of gas, sufficient to produce explosion, ample ventilation was provided and maintained throughout. At first, this heading also was operated on the plan of exhausting foul air and powder smoke. As the heading advanced, however, the temperature

rose to such a degree that some relief became necessary. In addition, a strong flow of carbonic gas was tapped, which required continual removal to keep the headings in an endurable condition. To overcome these difficulties an inclined shaft nearly 700 ft. in depth was driven at a point 8800 ft. east of the west portal, Fig. 17. This shaft was connected to the headings by two lines

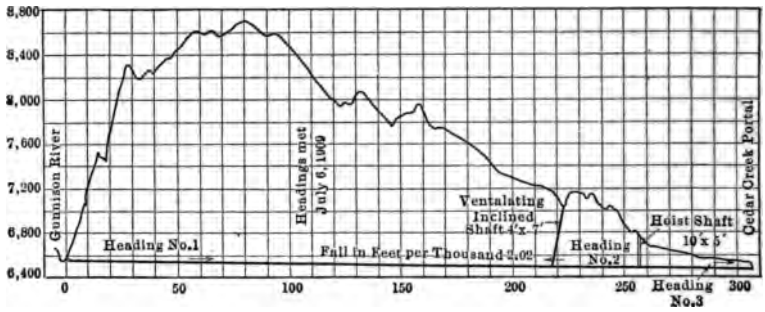


FIG. 17.—Profile of the Gunnison tunnel.

of 12-in. pipe, the pipe lines being used intermittently as suction lines and as pressure lines. Immediately after blasting the blowers were operated for an hour, more or less, as suction fans, drawing foul air from the heading. As soon as the powder smoke was well cleared out, the blowers were reversed and blew a draft of cool air into the heading.

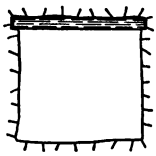
The following table gives the length of several tunnels or headings driven without artificial ventilation:

Name of tunnel	Area of tunnel, sq. ft.	Length driven without artificial ventilation, ft.
Tashenberg	54	330
Rudersdorf	118–160	328
Heinsberg	100	655
Giersky	55	655
Pfaffensprung	59–86	1100
Rehberg, top heading	35	165
Rehberg, bott. heading	62	460
Ricken	65	260
Schnee	60	820
Prato	108	2200

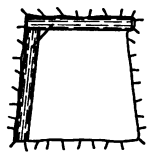
Timbering Headings and Tunnels of Small Cross Section

According to the purpose of the bore, the timbering may be of permanent or temporary nature. Bottom headings of railroad

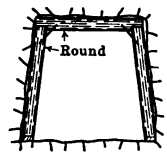
tunnels or of tunnels of large cross section are timbered temporarily, for a relatively short period of time; therefore, the timber sets are made of simple design and as light as possible. According to the intensity and direction of ground pressure, the types illustrated by Figs. 18 to 25 are used. In the Simplon tunnel, the type illustrated by Fig. 22 was used in the bottom heading; it consisted of two round vertical posts and of a square cap, this timbering method being used extensively in connection with long tunnels abroad.



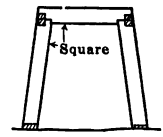
One-piece set
FIG. 18.



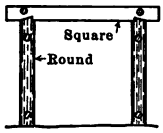
2-piece set
FIG. 19.



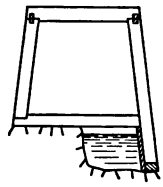
3-piece set
FIG. 20.



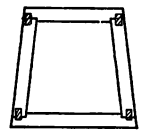
3-piece set
FIG. 21.



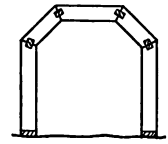
Set used in Simplon tunnel
FIG. 22.



Set for tunnels with drainage ditch
FIG. 23.



4-piece set
FIG. 24.



Arch set
FIG. 25.

In mine and drainage tunnels, without masonry lining, the types illustrated by Figs. 18 to 24 are used. When the span increases, and when the pressure of the ground becomes such as to make the use of horizontal caps prohibitive, the type shown by Fig. 25 is advocated, the size of the timbers being usually 8 × 8 in., 10 × 10 in. and 12 × 12 in. in remote cases.

When side pressure occurs, or when the floor of the tunnel has a tendency to rise, a sill is provided as shown by Fig. 24, for instance. When the pressure becomes such as to make the use of timber inadequate, sets built up of structural steel sections are used, as was done in the Simplon and Karawanken tunnels.

The timber sets referred to above are used in connection with bores driven through relatively solid rock, requiring no lagging, except that necessary to prevent falls of rocks loosened by blasting.

When the timbering is to be embedded in the lining, as was done, for instance, with the Strawberry and Elizabeth tunnels, Figs. 16 and 26, respectively, square timber is used.

Timbering used for temporary purposes or to be embedded in concrete is usually left untreated, *i.e.*, no prevention is made to prevent decay, except that the bark of round timber is usually

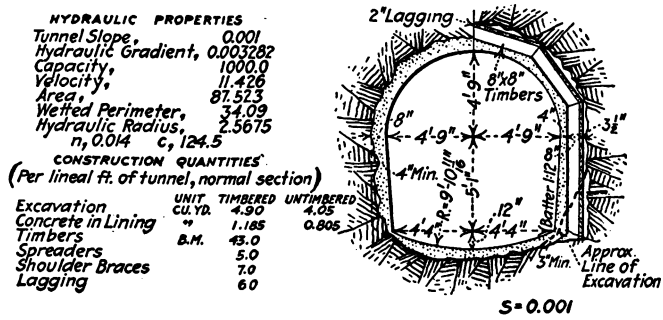


FIG. 26.—Elizabeth tunnel.

removed, and that the timber is used when relatively well seasoned. Timbering to be embedded in concrete should especially be well seasoned, so as to avoid shrinkage, thereby causing voids to be formed within the lining.

Permanent timbering as used in connection with unlined mine and drainage tunnels is used both treated and untreated, although there is a marked tendency now to treat timbering with creosote or zinc chloride, especially in those sections of the country where timber is scarce.

Cost of Driving Tunnels of Small Cross Section

The cost of driving headings and tunnels of small cross section is relatively high, when compared with that of driving railroad tunnels, for instance, where the unit cost of excavation runs from about $3 to $7, whereas that of small bores runs anywhere from $6 to $12 and sometimes more, according to the location, wages prevailing, etc.

On one hand, tunnels driven in the western states, far from railroad facilities, very often involve heavy development and transportation charges, but, in general, the men "stick" to the job for a longer period of time than in the eastern states, and thereby become more efficient in their respective work. Also, a better class of tunnel men is available, where the wages are comparatively higher than in the eastern states.

Chiefly from Bull. 57 of the Bureau of Mines.

Name of tunnel	Cross section	Cost per lin. ft.
Gunnison	12.3×10.5	$70.66
Laramie Poudre	9.5× 7.5	39.54
Elizabeth, N. side	12 ×12	43.55
Elizabeth, S. side	12 ×12	38.00
Lucania	8 × 8	23.00
Mission	6 × 7	19.91
Rawley	8 × 7	19.87
Roosevelt	10 × 6	27.27
Stilwell	7 × 7	23.38

The cost of driving 500 lin. ft. of the Strawberry tunnel, during the month of November, 1910, was as follows:

	Cost per lin. ft.
LABOR:	
Engineering	$0.500
Superintendents	0.500
Shift bosses	1.308
Timekeepers	0.100
Drillmen	2.843
Miners	0.187
Muckers	2.860
Track- and dumpmen	0.536
Skinners	.....
Timbermen	0.609
Miscellaneous	0.087
MATERIALS:	
Powder, fuse, caps	3.009
Lumber	0.413
Oil, candles	0.230
Vent pipes	0.720
Track and ties	0.523
Air pipe	0.219
Drill repairs	0.014
Miscellaneous	0.040
Machine shop expense	0.899
Blacksmith shop expense	0.988
Corral expense	0.088
Power	3.763
Depreciation, tramway plant	0.200
LABOR:	
Motorman and brakeman	1.080
Electrician and blower man	0.143
Disabled employes	.....
Equipment depreciation	1.000
Camp expenses	0.545
General expenses	3.292
Total per lin. ft.	$26.696

The cost of driving 830 lin. ft. (2856 cu. yd.) of the 13.5 ft. × 7-ft. heading of the Tallulah Falls tunnel was as follows:

Items	Cost per cu. yd.
Labor	$4.18
Overhead charges	0.295
Blacksmith's repairs	0.107
Machinist's repairs	0.135
Supply house labor	0.043
Office force	0.082
Outside force	0.12
Drill steel	0.06
Blacksmith coal	0.035
Mules feed	0.051
Freight	0.144
Drill repairs	0.324
Piping and fittings	0.09
Miscellaneous supplies	0.076
Dynamite	0.035
Exploders	0.051
Connecting wires	0.033
Gasoline	0.013
Lubricating oil	0.033
Tamping bags	0.006
Total	$6.913

The cost of driving the 6235-ft. long Rawley tunnel, 8 ft. wide at the base, 7 ft. at the top and 7 ft. high, is as follows:

Items	Cost per lin. ft.
Drilling and firing	$5.25
Mucking	2.16
Tramming	1.13
Track and pipe	0.44
Miscellaneous expenses	1.44
Power plant	2.50
Blacksmithing	0.73
Miscellaneous surface work	0.83
General expenses	1.98
Permanent plant	3.24
Timbering	1.18
Boarding house, debit balance	0.04
Total	$20.98
Less salvage	1.11
Total	$19.87

CHAPTER IV

TUNNELS OF MEDIUM CROSS SECTION

Tunnels under this classification have been driven chiefly in connection with water supply systems, such as the Croton and Catskill aqueducts, both forming part of the New York water supply system, or such as the Milwaukee intake tunnel, or else driven in connection with water power developments such as the Niagara Falls, Kern River, Great Western and Tallulah Falls developments, together with many others in this country and abroad.

DRIVING METHODS

Tunnels up to about 12 ft. high are excavated either by driving a bottom heading first, having the full width of the

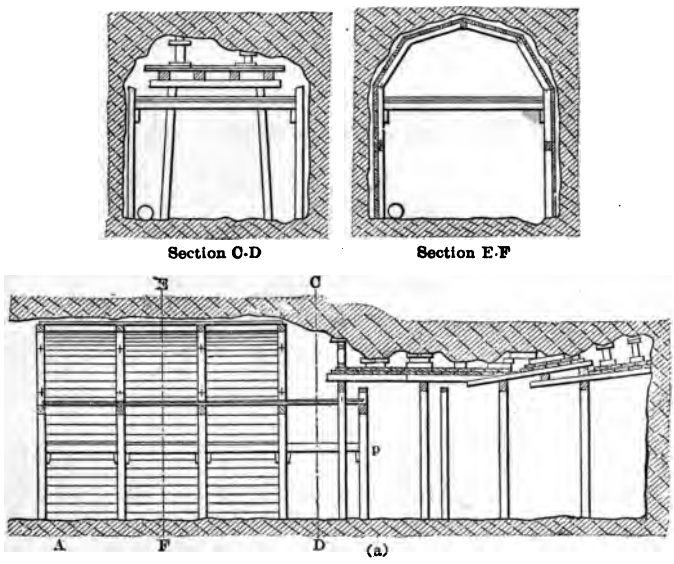


FIG. 27.—Sequence of excavation, Elizabeth tunnel.

finished tunnel, or a fraction thereof, the roof being stoped down in a next operation, as was done for instance in the Elizabeth tunnel, Fig. 27, or by driving a top heading and a small bench 3 or 4 ft. high, as in the Strawberry tunnel, Fig. 16.

All pressure tunnels, and most of the grade tunnels of the Catskill aqueduct system, were driven with the top heading and bench method, with a few exceptions only. This method enabled monthly progress of 250 to 300 ft. to be made in igneous rocks, and of 400 to 500 ft. in sedimentary rocks such as shales, etc.

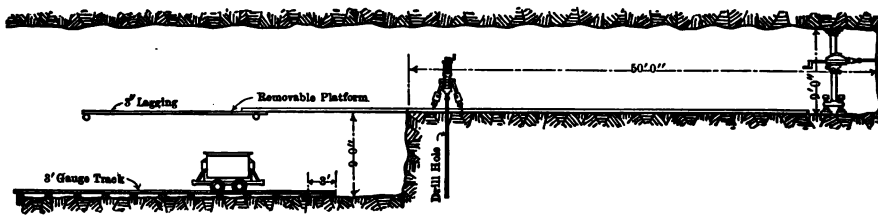


FIG. 28.—Top heading and bench method.

In driving the Hunters Brook tunnel, the following methods were tried: The first method used consisted in driving a bottom heading about 15 ft. wide and 8 ft. high, over a length of about 40 or 50 ft., and then in setting up the drills over a muck pile, in front of the heading's mouth, drilling and stoping down the material overlaying the heading. This method was soon abandoned however, being too costly, as work could proceed at one point only.

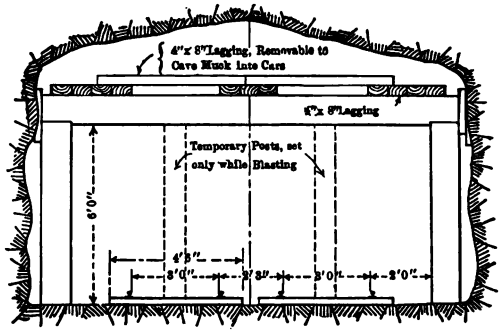


FIG. 29.—Bottom heading, Hunters Brook tunnel.

Driving then proceeded with a top heading and bench, Fig. 28, and thus 677 ft. were driven on the north side and 716 ft. on the south side, the average progress being 84 and 126.5 ft. per month, respectively. This method of driving was done at a loss to the contractor.

The north side of the bore was then closed, and driving proceeded with two 8-hr. shifts and three mucking shifts. The new method tried consisted in driving a bottom heading 8 ft. wide and 9 ft. high. This permitted only one line of track in the heading, as the track was 36-in. gauge. As mule haulage had to be relied upon, the muck could not be taken out fast enough and it became necessary to use two tracks. The heading was then widened to 15 ft., Fig. 29. It was driven with four Ingersoll Rand drills, mounted on column. The rounds varied from sixteen to twenty-eight holes, according to the rock. Cut holes were driven 6 and 7 ft. and breakers 5 ft. deep. After a blast, four muckers cleared the heading in about 3 hr., and the heading was thus cleared twice a day. The powder, 60 per cent. forcite, averaged 7.5 lb. per cu. yd. in the bottom heading. An effort was made to cut down the quantity of powder, but this proved to be a false economy, as the muck broke large and more labor was required to handle it.

Thus, 6916 cu. yd. were excavated at a cost of $3.40 per cu. yd. not including haulage and overhead charges.

The top heading, Figs. 30 to 32, was excavated as follows: A timber gang working on day shift only put up the temporary sets required for the stope. The top of the platform was 7.5 ft. above the tunnel floor. The bottom heading having been driven 9.25 ft. high, there was left a space of 21 in. above the temporary timbering to break up.

In the stope, two drills were used, mounted on an 8-ft. cross bar. The round varied from twelve to sixteen holes, which were all breakers. The bottom holes were

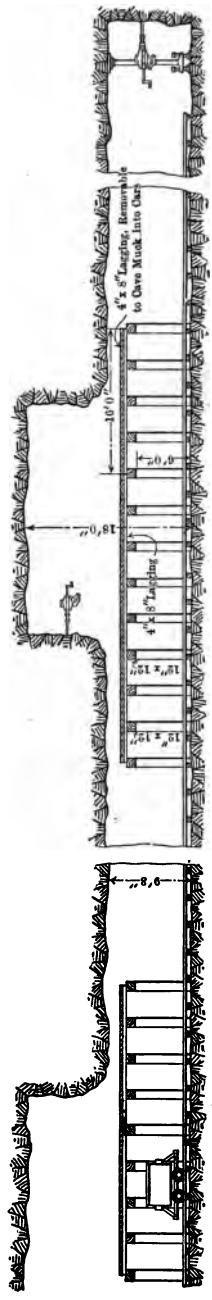


FIG. 30.—Bottom heading and stope method.

fired first, lightly, then the next row above and so on to the top. The timber caps were supported by extra posts, Fig. 29, during shooting, and the muck was held on the platform. It was then rapidly caved into the cars, through the lagging, by two men. This operation left the stope incomplete, as shown by Fig. 31. One drill runner, using a stoper drill, did all the trimming necessary. The temporary sets and lagging were regularly moved forward from behind the stope, to be reused. In order to facilitate the work of stoping, it was found expedient at

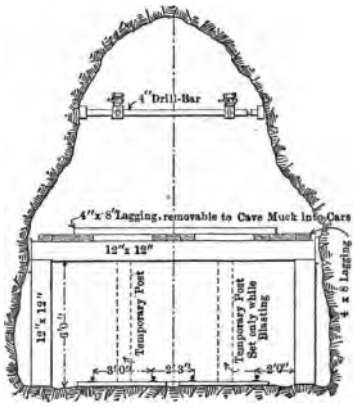


FIG. 31.—Method of stoping out top, Hunters Brook tunnel.

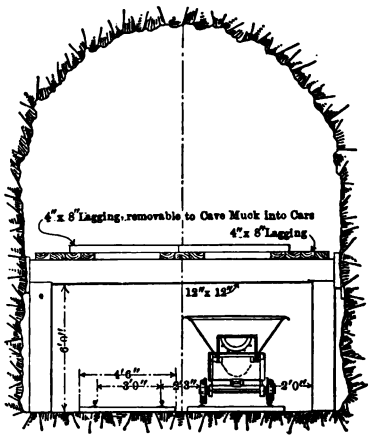


FIG. 32.—Completed tunnel, Timbers to be moved forward.

times to separate the drilling, mucking and trimming operations in the top heading. This was accomplished by putting up a raise about every 300 ft. as shown in Fig. 30, and thus drilling was going on in one, mucking in another and trimming in the third.

During 5 months, there was stoped from the top heading a yardage equal to that of the bottom heading, but at a labor cost, including blacksmith, and all costs of temporary timber platform and maintenance thereof, of $1.69 per cu. yd., making an average cost per cu. yd. for the complete bore of $2.54, in the cars. The powder consumption in the stope, for the same period, was 2.5 lb. per cu. yd.

Economy and Elasticity of the Method

The advantages of this method are several. The most important is that 50 per cent. of the muck is handled from the stopes directly into cars, by gravity, at a minimum of labor and cost.

By the old method all of the muck in the top heading is shoveled into wheelbarrows and wheeled the whole length of the bench and beyond, to be dumped into cars. This requires a large crew of muckers and wheelbarrow men for the top heading besides an equally large crew to muck the bench.

Timbering is a much more simple process by the mining method. It can be kept close to the breast without injury to timbers, and wall plates are unnecessary, each set being built up from grade; neither need there be any delay. By the old method, wall plates must be placed first, which is a slow operation; then the arches are placed and later, when the bench has been blasted out at considerable risks sometimes to the upper timbering, posts are set under the wall plates. Very frequently timbers are blown out by the heavy blasts of the cut in the top heading. All this is avoided by the mining method, at least to a large extent.

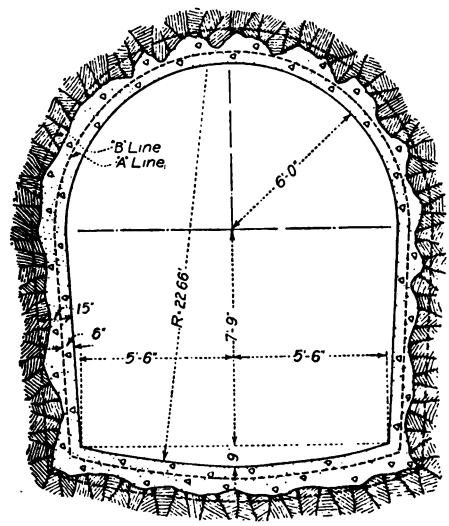


FIG. 33.—Cross section, Tallulah Falls tunnel.

Finally, there is more elasticity. The greatest effort for progress is concentrated in the bottom heading, to which everything else gives way; for here there is only one point of attack possible. If for any reason the top falls behind, it does not matter greatly.

Progress of the bottom heading is not thereby impeded and the top may be attacked from as many new raises as may be required to make up lost time, whenever it is convenient to do so. By the old method, however, if the bench falls behind, work in the top heading is immediately made more difficult and costly.

The Tallulah Falls tunnel, Fig. 33, has an area of 151 sq. ft. within the lining. A circular section would have been more favorable to serve the purpose intended, but as no external hydrostatic pressure of any magnitude was anticipated, and for the

sake of convenience in driving and lining the bore, a section with straight battered side walls was adopted. The tunnel was driven on a 2 in. 1000-ft. grade, through quartzite, dipping downstream at an angle of 22°, with occasional mud seams. The ground stood well generally, and only 5 per cent. of the tunnel length required timbering.

For the purpose of expediting the work, it was found desirable to drive the tunnel from the intake and forebay ends, Fig. 4, as well as from two adits 7 ft. high and 13 ft. wide, 105 and 217 ft. long, driven on a 1 per cent. grade.

Seventy-five per cent. of the tunnel was driven with a top heading and bench and the balance with a bottom heading, the overlaying material being stoped down on the heading floor. The average progress for heading and bench work during the year 1912 was 30 and 38 ft. respectively, per week (6 days). Twice the progress was made in stoping work as in bench excavation at a less cost of about 50 cents per cu. yd. During the month of April, 1912, about 1784 cu. yd. of bench material were excavated at a cost of $4.315 per cu. yd., and during May of the same year, 3807 cu. yd. were stoped down at a cost of $3.79 per cu. yd., or at a lesser cost of 52 cents per cu. yd. The comparative cost of bench and stoping work was as given in the following table:

Items	Cost per cu. yd., stoping work	Cost per cu. yd., bench work
Labor	$2.415	$2.965
Supt. and walking bosses	0.141	0.067
General expenses	0.036	0.101
Office force	0.103	0.085
Storeroom force	0.027	0.028
Repairmen	0.115	0.102
Carpenters	0.053	0.050
Dynamite	0.339	0.416
Exploders	0.029	0.038
Connecting wires	0.015	0.014
Kerosene	0.002	0.002
Lubricating oil	0.013	0.012
Tamping bags	0.002	0.002
Lamps	0.011	0.010
Piping and fittings	0.015	0.029
Drill repairs	0.204	0.095
Miscellaneous supplies	0.041	0.063
Drill steel	0.107	0.080
Blacksmith coal	0.027	0.027
Freight	0.063	0.079
Feed	0.031	0.050
Total	$3.789	$4.315

The cost of excavating 39,831 cu. yd. of tunnel was as given in the following table:

Items	Cost per cu. yd.
Labor	$3.833
Explosives	0.604
Lubricants	0.019
Piping	0.026
Drill repairs	0.172
Miscellaneous supplies	0.237
Freight	0.087
Transportation	0.247
Liability insurance	0.181
Miscellaneous charges	0.066
Depreciation on equipment	0.150
Power	0.306
Total cost per cu. yd.	$5.928

Table giving name and length of tunnels of small and medium cross section:

Name of tunnel	Length, ft.
Gunnison	30,645
Laramie Poudre	11,306
Elizabeth Lake	26,870
Tallulah Falls	6,666
Oneida	7,030
Coronade	6,300
Mission	19,560
Rawley	6,235
Cincinnati Waterworks, land tunnel	22,264
Cincinnati Waterworks, intake tunnel	1,426
Roosevelt	15,700
Strawberry	19,100
St. Louis Waterworks	2,253
Stilwell	2,950
Marshall Russell	11,000
Central	9,000
Big Creek	22,000
Lucania	12,000
Newhouse	22,000
Hunters Brook	6,150
Coquitlam	12,650
Bonticou	6,823
Breakneck	1,054
Bull Hill	5,360
Millwood	4,750

Lining Tunnels of Small and Medium Cross Section

A large proportion of tunnels of small and medium section are used for water-conveying purposes, and in order to obtain tightness and also to decrease frictional resistance, water-conveying tunnels are lined usually with concrete or brick masonry.

In certain instances, when the material penetrated is solid, hard, impervious and not liable to decompose, due to chemical action when coming in contact with water, water-conveying tunnels are left unlined, ample area being provided to make up for frictional resistance.

In grade tunnels, only the invert and side walls are lined sometimes, when the roof of the bore is stable. On certain occasions, provision is made for the future insertion of a brick or concrete block arch lining.

As a bore increases in sectional area, it becomes necessary to line it throughout the periphery, especially in tunnels subjected to internal or external hydrostatic pressure, or to resist ground pressure also.

The lining of water-conveying tunnels is usually given a smooth finish, thereby increasing their carrying capacity and for the same reason the wet perimeter is made a minimum. In Europe, it is the practice to give the lining a coating of 1 to 1–½ in. cement mortar, immediately after the forms have been removed, that is, when the concrete is yet green. This method of procedure is rather costly, especially where wages are high; furthermore, when external hydrostatic pressure is high, flaking of the coating is liable to occur. Yet this method enables a very smooth finish to be obtained, an advantage which, in certain instances, should be given due consideration.

Lining the Gunnison Tunnel

A few months after the bore had been driven, it became evident that the ground was ravelling rapidly under the influence of the air and that the heat and moisture of the tunnel were rapidly destroying the timbers. Plans were made at once to begin concrete work, Fig. 34.

For placing the concrete, a traveler, Fig. 35, was used. This traveler was provided with a hoist set in line with the tram tracks in the bore. The traveler permitted the passage of muck cars underneath and furnished a platform upon which the concrete

cars were dumped after being hoisted to the proper height. After dumping, the concrete was remixed and shoveled into place. As many as 1800 ft. of tunnel were thus lined in 1 month, at a gross cost of $6.50 per cu. yd., incuding cement at $3.15 per barrel, all labor, power and superintendence included.

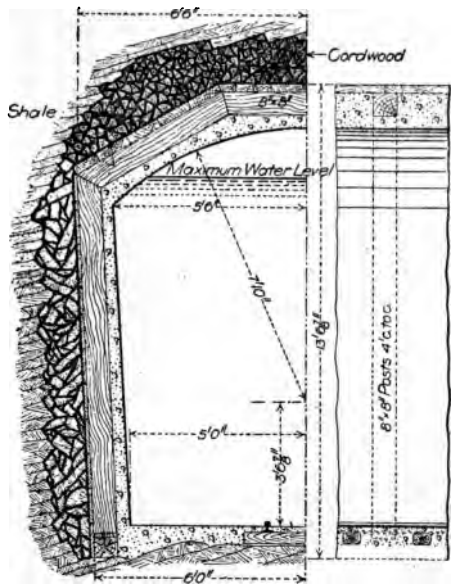


FIG. 34.—Cross section, Gunnison tunnel.

Lining the Tallulah Falls Tunnel

Work on the lining (see Fig. 33) was not started until the tunnel had been practically completely excavated. About 120 ft. of tunnel invert was concreted first at adit No. 3, shown in Fig. 4, and Blaw collapsible steel forms were then erected and concreted. It was soon found out that it would be preferable to concrete the side walls and arch first, and later on the invert, and this procedure was then followed throughout.

A total length of 240 lin. ft. of Blaw forms were used, the lining being carried on simultaneously at three points. Three concreting machines furnished by the Concrete Mixing & Conveying Co. were installed and operated by air at 100 lb. pressure (see Fig. 36). The best results were obtained when conveying concrete to the steel forms, as shown in Fig. 37, erected in 20-ft. length only, through 6-in. diameter spiral galvanized iron pipes. The concrete was a 1:3:5 mixture, the aggregate not being over 2 in. in size. In using the concrete machines, great care had to be exercised in order to prevent the formation of voids within the lining, as its thickness was relatively small. In general, it was found that a somewhat better finish would have been obtained had the lining been given a greater thickness, as it was somewhat difficult to clean thoroughly the forms after these had been used. However, the results obtained were satisfactory for the purpose

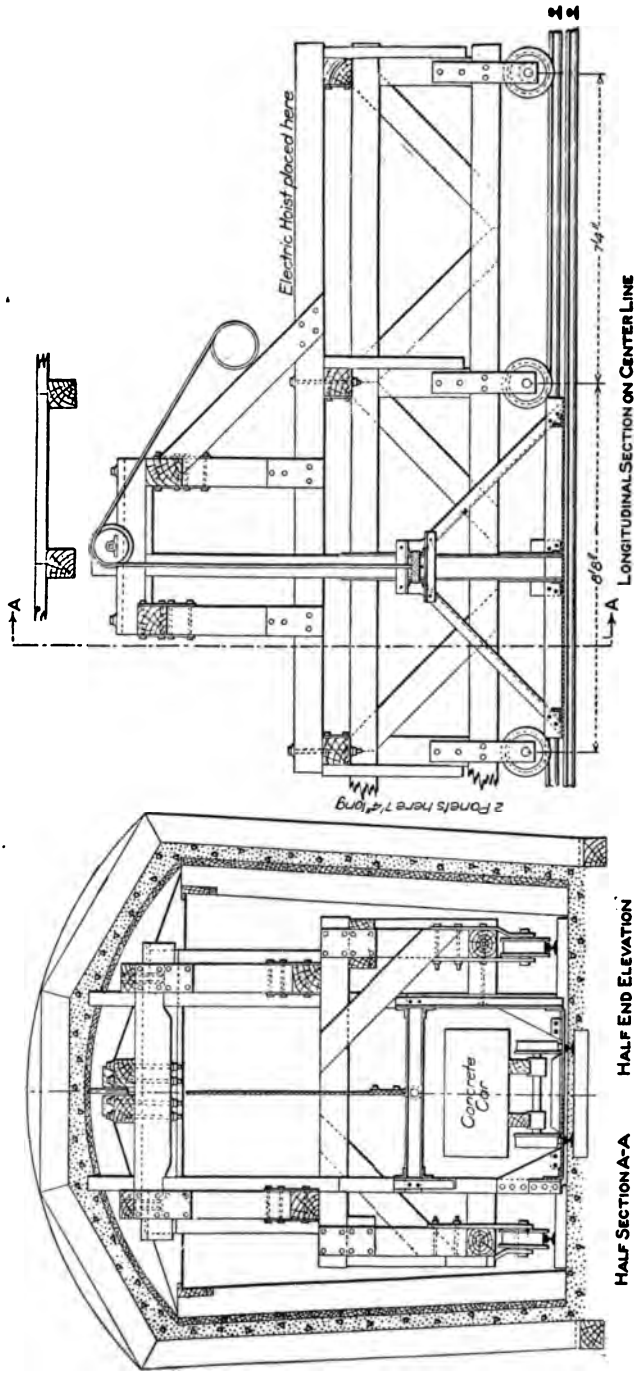


FIG. 35.—Traveler used in lining the Gunnison tunnel.

intended. In wet places the concrete was somewhat honey combed, but this defect was corrected during the grouting process.

In places where the tunnel roof was high, it was found more economical to use concrete rather than spalls for back filling, inasmuch as all voids were to be grouted.

The average progress of concreting varied from 30 to 60 ft. per week (6 days), the average for the whole tunnel being about 40 ft. The invert was laid without air concreting machines, as it was found that, in order to obtain satisfactory results, the concrete had to be delivered in a confined space. The invert was laid at a rate of about 745 ft. per week. The cost of the concrete lining was as follows, cement costing $1.80 per barrel:

Items	Cost per cu. yd.
Labor	$5.120
Cement	2.995
Miscellaneous materials	0.411
Lumber	0.138
Freight	0.066
Transportation	0.157
Insurance	0.168
Royalty on concreting machines	0.420
Miscellaneous expenses	0.106
Crushing rock	2.020
Quarrying rock	0.870
Plastering concrete	0.206
Cleaning up tunnel	0.382
Total[1]	$12.041

Grouting: The specifications called for a mixture to be used for this purpose, consisting of 1 to 1–½ parts sand to 1 part cement. Grout and vent pipes 1–½ in. diameter were provided in the tunnel arch, or in other places where necessary, 15 ft. apart, more or less. Four grouting machines were used for this purpose, under 40–60 lb. pressure per sq. in. Little trouble was encountered, although in a few places local flaking of the lining occurred where voids had been left. In wet places the grout oozed through the honeycombed concrete, thus making a somewhat rough surface, which was smoothed up later on. The cost of grouting was about $1.10 per cu. yd.

[1] Concreting forms and depreciation on equipment not included.

Lining the Pressure Tunnels on the Catskill Aqueduct

Beyond the limit of the City of New York, the pressure tunnels of the Catskill aqueduct have a circular cross section, generally with an internal diameter of 14 ft. 6 in. (Fig. 38). The specifications require that no rock is to project within a line 12 in. from the waterway. The thickness of the lining within the pay line varies from 10 to 25 in. In general, the lining had an average thickness of 18 to 20 in.

Concreting was carried on by laying an invert about 5 ft. wide first. In the Rondout pressure tunnel, the concrete was brought over with cars and dumped on a platform, hence wheeled with wheelbarrows over a runway, and dumped on the floor of the tunnel, between side boards spaced 5 ft. apart. In the Walkill pressure tunnel, the concrete was dumped directly from the cars into the forms, thereby avoiding rehandling. When the concrete had hardened sufficiently, it was shaped to the required curve with trowels. In general the invert was laid first from one shaft to another, before concreting the side walls and arch.

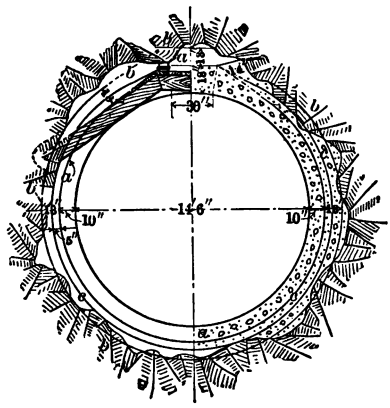


FIG. 38.—Pressure tunnel, Catskill Aqueduct.

Blaw steel forms were used to concrete these, and they were used in lengths varying from 40 to 60 ft., although it was found that a 60-ft. length could be handled to advantage. These forms were carried on a truck or carriage, running on the concrete invert. After the invert had been laid, in the manner referred to above, the side walls were built up to the springing line, and for this purpose an inclined track, Fig. 39, enabled cars to be raised from the tunnel grade up to a platform located at the elevation of the springing line of the tunnel. In the Walkill pressure tunnel the inclined track, mounted on trucks, was about 90 ft. long, and in the Rondout pressure tunnel, about 75 ft. long. Air or electric hoists were used to haul the cars up the incline. In the Rondout tunnel, the side walls were concreted first, using

FIG. 36.—Concrete gun used for lining Tallulah Falls tunnel.

FIG. 37.—Pipe leading from concrete gun to forms, Tallulah Falls tunnel.

(*Facing page* 42.)

FIG. 39.—Completed lower half of concrete lining and inclined track. Rondout pressure tunnel.

FIG. 40.—Collapsible steel forms carried on carriages to line tunnel roof, Rondout pressure tunnel.

sections of forms 60 to 80 ft. long. Then the forms were turned over to concrete the arch, and to serve this purpose, they were carried on carriages, as shown in Fig. 40.

The arch was concreted as follows: Concrete was brought over in cars and dumped on the platform at springing line elevation, hence shoveled into the forms. These were struck within 20 or 24 hr. after having been concreted. To concrete the arch, the panels of the forms were removed at the top of the form, and put in place again as concreting reached a higher elevation. Wooden bulkheads were used at the end of the form sections. In the Walkill pressure tunnel and on other sections of the aqueduct, concreting proceeded as follows: A section of side wall and arch forms was erected first and in front of these a section of about the same length of side-wall forms. Concrete was conveyed by cars up the incline, dumped on the platform and shoveled into the forms of the first section, *i.e.*, in the side-wall and arch forms. The concrete left over was shoveled into the second set of side-wall forms, so that both sections were concreted in about the same length of time, that is, from 14 to 16 hr., usually.

In wet sections, drip pans, made of sheet iron and drained by a pipe, were provided so as to avoid making porous concrete.

Grouting

Several methods of grouting were used in various sections of the aqueduct. In general, grout mixed in the proportion of 1 part cement to 1 part sand was used under pressures varying from 40 to 300 lb. per sq. in.

Grout and vent pipes had been provided in the side walls and arch, and grouting usually started at a low point under low pressure and finished under high pressure at the top of the arch. A grouting outfit consisted of Caniff tank grouting machines mounted on a truck, with a platform enabling the operators to reach the roof of the bore.

In order to divide the lining into sections, for the purpose of grouting, cut-off walls were provided 40 to 60 ft. apart, with the hope to be able to confine grout between two such walls. Actually little or no result was gained thereby, as the cut-off walls allowed the grout to pass beyond them, thus spreading in the next section, before the section considered had been thoroughly grouted.

On certain occasions it was necessary to go several times over a tunnel section, grouting and re-grouting it, until a satisfactory job was obtained. Some trouble was encountered at the vertical joints of two sections of the lining, where leaks developed, due to the contraction of the concrete.

FIG. 41.—Method of keying arch, Catskill aqueduct pressure tunnels.

(*Facing page* 44.)

FIG. 45*a*.—Timber lining, St. Paul Pass tunnel.

CHAPTER V

RAILROAD TUNNELS OF MODERATE LENGTH

The largest proportion of railroad tunnels belong to this class, their length varying from 100 or 200 ft. to a mile or two. During the past 10 years, there has been a tendency among railroad builders to do away with short tunnels, generally not deeply overlaid, substituting these with open cuts and, in several instances, existing short tunnels have been converted into open cuts.

DRIVING METHODS

Top Heading and Bench Method

In this country, the top heading and bench method has been used almost exclusively, especially in solid materials, and there is no doubt that, owing to the kind of labor available and wages prevailing, this method is the most economical one for tunnels less than 3 miles long, not deeply overlaid or subjected to heavy ground pressure or high rock temperatures. Generally, the sequence of excavation is as follows: In solid rock, the top heading is driven the full width of the bore, its height being 8 or 9 ft.; the bench follows then at a distance of 30 to 60 ft.

In shattered rock, where slips are liable to occur, a heading 9 to 10 ft. wide is driven first, followed by a timber gang and later on by a trimming crew, whose duty is to widen the heading to full width.

Sometimes the heading is driven first from portal to portal, but this method, although simplifying the driving operations, is costly, owing to the fact that the superintendence and overhead charges are spread on the heading excavation alone and then on the bench, instead of on both simultaneously.

Another method consists in driving a bottom heading first, having the width of the bore, from portal to portal, and then drilling bore holes on a slight batter, Fig. 42, through the material overlaying the heading, and stoping it on the tunnel grade.

Owing to the width of the heading, it is obvious that this method can only be used successfully in solid materials, but as stoping can only be started when the heading has been driven through, the remark, applying to top headings driven first from portal to portal, holds good here too.

Generally, four to six drills mounted on columns are used in the heading, and two to four drills, mounted on tripods, do all necessary bench work, as shown in Fig. 28. The bench is usually excavated in two operations: In tunnels driven through hard materials, requiring little or no timbering, thus keeping the height of the bore down to a minimum, deep vertical or slightly inclined bore holes are drilled from the top of the bench down to within 3 or 4 ft. from the tunnel grade, and then sloping holes are drilled perpendicularly to the face of the bench (Fig. 43). When the bore is high, the bench is excavated in two lifts, as illustrated by Fig. 44. The muck from the heading is conveyed to the face of the bench in wheelbarrows or in

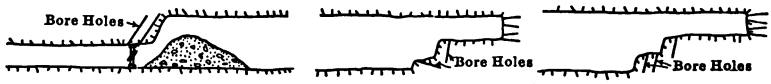


FIG. 42. FIG. 43. FIG. 44.

FIG. 42.—Stoping method of excavation.
FIG. 43.—Method of excavating low bench.
FIG. 44.—Method of excavating high bench.

cars of small capacity, and dumped on the tunnel floor or else into cars, a platform being provided for this purpose (Fig. 28).

The material excavated from the bench is loaded into cars by means of a steam or air operated shovel of 1 to 1-½ cu. yd. capacity, the cars used for haulage purposes being usually of 3 to 5 yd. capacity.

ST. PAUL PASS TUNNEL.—Fig. 45. This bore, 8750 ft. long, was driven during the years 1907–1909, through the Bitter Root Range, on the Montana-Idaho state line, by the top heading and bench method. The material was, in general, a laminated quartzite with talc between the strata, but the character changed often, which necessitated changes in the method of conducting the work. The heading was, when the material permitted, driven with a full face, following it as closely as practicable, usually from 50 to 60 ft., with the timber lining, but often it became necessary to drive small side drifts for the wall plates and carry the arch timbers within 2 ft. of the face.

Usually, six drills were operated abreast, driving the full heading face, two on one column about 3 ft. each side of the center line and one on a column in each corner. These were followed by a trimmer taking off all points to obtain the correct section. This was followed by a special timber crew, erecting the timber lining.

The heading material was shoveled into 1-yd. end dump cars, pushed by hand to a chute back of the bench and dumped into

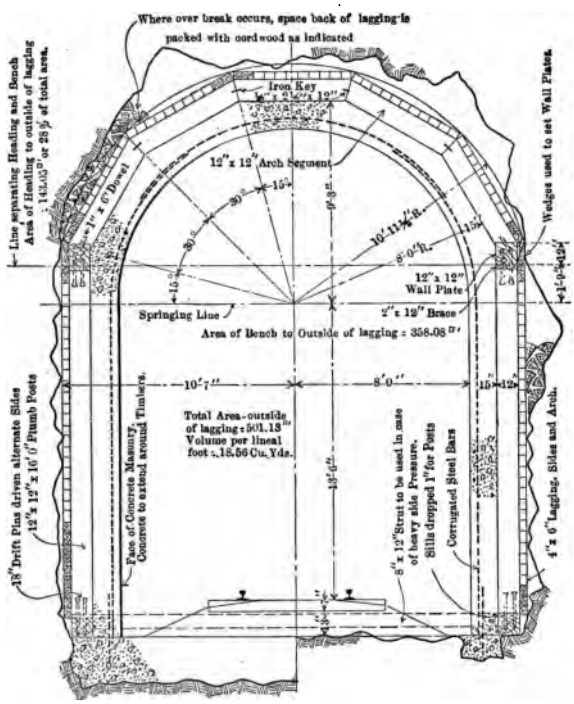


FIG. 45.—Cross section of St. Paul Pass tunnel.

cars on a side track on the bench level. The heading track was supported by timbers spanning the tunnel and resting on the wall plates. The bench was driven by four and at times by five drills working on the floor level; occasionally, it was necessary to drill down holes and also at some places, where the material was particularly hard, it was necessary to take out a sub-bench. The air shovels loaded the bench material into 1-½-yd. cars, which were spotted by horses, but hauled out of and into the

tunnel by two 15 H.P.-electric locomotives at each end, from eight to eleven cars to the train.

The heading muck cars were run out on a platform over the bench workings, a distance of 150 ft., to a muck chute leading to the tunnel trains on a track below. This platform was built ahead, as the bench progressed and new chutes were added as required. The progress during the year 1908 was as follows:

Month	Heading progress		Bench progress	
	East, ft.	West, ft.	East, ft.	West, ft.
January	200	159	246	50
February	247	285	229	192
March	218	286	205	218
April	259	275	217	193
May	241	329	298	263
June	203	333	325	309
July	249	295	207	319
August	318	310	200	415
September	306	254	218	333
October	320	227	272	342
November	340	268	328	527
December	357	298	284	304

The ventilation of the tunnel was accomplished by the use of an Exeter fan operated as an exhaust, exhausting through a 24-in. galvanized iron pipe, made up of 30-ft. lengths, with flanged joints and paper gaskets. The end of this pipe was maintained at a distance behind the bench sufficient to prevent the pipe from being dented and perforated by shooting. A No. 2 Root blower was also operated to pump fresh air into the tunnel, through an 8-in. galvanized iron pipe. This pipe was carried close to the heading face.

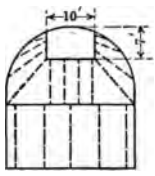


FIG. 46.—Drilling diagram, Gallitsin tunnel.

GALLITSIN TUNNEL.—This single-track bore, on the Penna. Ry., near Altoona, Pa., was driven as illustrated by Fig. 46. A heading 7 ft. high and 10 ft. wide was driven first near the crown of the arch and the rock was excavated by means of a center cut and parallel side holes, the number of these depending upon the rock penetrated. The three different points of attack, that is, heading, top and bottom benches were kept about 10 ft. apart. Blasting was ef-

fected by starting with the bottom bench first and finishing with the heading.

CASCADE TUNNEL.—This single track bore, driven through the Cascade Mountains, is 13,813 ft. long. The material penetrated was hard basalt. The rock was excavated by the top heading and bench system, a wide heading being driven first. The material excavated from the heading was wheeled over to a timber platform and dumped into cars on the tunnel grade.

For the purpose of handling the bench material, a hoist engine, located on the platform loaded the larger rocks into cars. The engine was used also to move the platform back and forth, see Fig. 47. The timbering consisted of a five-segment arch set spaced from 2 to 4 ft. center to center.

All hauling was done with electric locomotives; trains of fifteen to twenty cars being run on a 1.7 per cent. grade, at a speed of

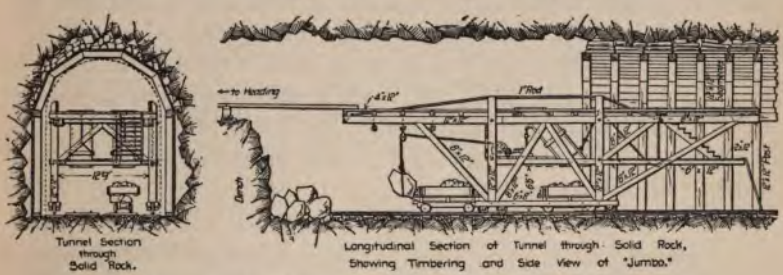


FIG. 47.—Method of excavation, Cascade tunnel.

10 miles per hr. There were two 24-in. tracks laid with 50-lb. rails. The tunnel was lit with electricity.

Air was exhausted from the heading through a 24-in. galvanized iron pipe, by means of a No. 9 Sturtevant fan, running at 1700 r.p.m. The pipes were made in 16-ft. sections, bolted together by cast-iron rings with paper washers between the rings.

Advantages and Disadvantages of the Top Heading and Bench Method

One of the chief advantage of this method lies in the simplicity of the driving operations, which do not require any special skilled labor, excepting mechanics, electricians, etc., and the engineering force is reduced to a minimum. As a matter of fact, on many instances, railroad tunnels up to a mile long, have been

driven without the assistance of a field engineer, save that of instrument men.

When little time is available to organize a tunnel force, to drive short tunnels, the method is well adaptable, especially when driving through solid material. Furthermore, the method of timbering and lining, in connection with the driving method is very simple also.

The chief disadvantage lies in the lack of flexibility in driving, for instance when heavy ground is encountered, or when striking a large inflow of water or gas. As soon as driving in the heading stops, the bench work and the timbering operations become affected, therefore this method of tunnel driving is not well adapted in connection with driving long and deeply overlaid tunnels.

The St. Paul Pass tunnel, for instance, is noted for the driving progress attained both in the heading and bench, and yet, the average daily progress hardly average more than 10 ft. per day. In single-track tunnels, and even in double-track bores, steam or air operated shovels do not work to advantage, as they have to be moved back and forth before and after blasting, and thus the best work done with a steam shovel, in tunnel work, averages hardly 300 cu. yd. per 24 hr.

Another disadvantage worthy of mention is that blasting in the heading, which is by far the most injurious blasting operation to the surrounding material, has a tendency to loosen or shatter the roof of the tunnel, thus necessitating more timbering than would be otherwise.

Drift Method

The method of driving tunnels through rock by drifting is used chiefly in Europe. Among tunnels driven with this method, in this country, mention should be made of the Murray Hill tunnel, one of the bores driven in connection with the New York Subway system.

It is a double-track tunnel, driven through mica schist, with occasional soft and unstable strata. The sequence of excavation is illustrated by Fig. 48. First a drift about 10 ft. wide and 8 ft. high was driven over a distance of 7 or 8 ft. It was then widened by excavating on each side, the portions marked 2. When 1 and 2 had progressed about 50 or 60 ft., part 3 was exca-

vated, and part 4 was stoped down on the tunnel floor, about 100 ft. back of the heading's face.

Sections 1, 2 and 3 were driven by using drills mounted on a vertical column. For the purpose of removing part 4, a timber platform about 10 ft. long, extending the full width of the bore and carried on tracks 23 ft. center to center was provided. The top of the platform was about 9 ft. above the floor of the tunnel, and it carried drills mounted on vertical columns. Before blasting, the platform was moved back and the blasted material fell on the floor, being loaded then into cars. Three narrow gauge tracks were laid on the floor of the tunnel, extending clear to the faces of the drifts.

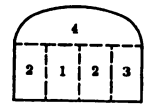


FIG. 48.—Sequence of excavation, Murray Hill tunnel.

Advantages and Disadvantages of the Drift Methods

The drift method of tunneling enables a bore to be driven practically through any kind of material, varying in hardness from hard to soft and from solid to loose; therefore the method insures against delays and contingencies such as are met with in tunnel driving.

Its chief disadvantage is that it requires a very elaborate organization, as all tunneling operations are carried on simultaneously at various points. The drift method necessitates an experienced tunnel crew and a relatively large engineering force; for this reason its use in this country has been very limited.

Cost of Railroad Tunnels

The cost of railroad tunnels varies according to the location, length, material penetrated, etc. Generally, tunnels accommodating two tracks cost from 25 to 35 per cent. more than single-track bores, that is, for tunnels of moderate length.

The unit cost of excavation is less for double-track than for single-track tunnels, as bench excavation is a larger proportion of the whole bore than in single-track tunnels. In general, the cost of rock excavation varies from $2.50 to $7 per cu. yd.

COST OF ST. PAUL PASS TUNNEL.—No complete records are available of the cost of the work, but the following figures are averages taken on the work when it was proceeding at the usual rate. They do not include interest and general office expenses.

Items	Cost per lin. ft.
Labor	$84.50
Power-house labor	7.00
Eng. and superintendence	3.00
Coal	4.16
Freight on coal	3.20
Plant, 50 per cent. of cost charged ag. work	15.00
Power-house repairs	8.75
Dynamite, heading	4.45
Dynamite, bench	2.76
Caps and fuses	2.10
Rubber clothes	4.62
Drill repairs, small tools, etc.	13.65
Water system	0.35
Camps	1.10
Total	$154.64

COST OF CASCADE TUNNEL.—Single track; length 13,813 ft.

Excavation	$123.40 per lin. ft.
Track and ballast	2.80
Engineering	4.30
Total	$130.50

COST OF STAMPEDE TUNNEL.—Single track; length 9950 ft.

Excavation	$93.17 per lin. ft.
Track and ballast	2.47
Engineering	5.00
Total	$100.64

Name of tunnel	Length, ft.	No. of tracks	Materials penetrated	Cost of excavation	
				Per lin. ft.	Per cu. yd.
Mount Wood	.....	1	Shale	$51.50	.....
B. & O.	624	1	Shale	53.30	.....
Busk	9395	1	Granite	70.00	.....
Webster	2240	1	Slate	67.00	.....
Kingwood	4100	2	Sandstone	78.00	.....
Pulasky	1067	1	Limestone	.....	$2.80
Musconetcong	4879	2	Gneiss	.....	6.00
Scranton	4747	1	Sandstone	.....	3.35
New Raton	2786	1	Sandst. shale	head.	1.68
				bench	5.50
Little Tom	.....	1	Sandstone	43.00	3.50

Timbering Railroad Tunnels of Moderate Length

The method of timbering tunnels driven in this country is known as the segmental arch rib system, illustrated by Figs. 45 and 45*a*.

The material used generally is square timber varying in size from 10 in. × 10 in. to 14 in. × 14 in., cut to size and shape before being taken in the bore, that is, ready for erection. In order to fit the bore as excavated, timber packing is used usually, placed back of the lagging.

Formerly, it was the practice of certain railroad companies, to line their tunnels with timber, so as to reduce the initial outlay of expenditure, but, as times goes on, and the timbering begins to reach the limit of its life, it becomes necessary to renew the lining, and the practice has been recently to build a permanent concrete or masonry lining.

Tunnel fires are not uncommon, caused either by locomotive sparks, although such cases are very remote, or by outside grass or underbrush fires, extending to the timber sets in the tunnel. In order to prevent the occurrence of such fires, a masonry portal has been built in certain instances, together with a concrete or masonry lining extending a short distance in the bore.

Recent practice favors lining tunnels with concrete or masonry, as the cost of relining a bore without interruption to train traffic is very onerous.

Advantages and Disadvantages of the System

The chief advantage of this system lies in its simplicity during erection. Then, it leaves the full section of the bore open for the concrete plant, and it enables steam shovels to be used in connection with the excavation work. It offers also less resistance to air for ventilation, and the dangers from fire during construction are also eliminated to a large extent.

The amount of timbering material is also reduced to a minimum, amounting to about 250 to 325 ft. B.M. and to 400 to 500 ft. B.M. for single- and double- track tunnels, respectively, the amount depending on the size and spacing of the sets.

The chief disadvantage of this system is its lack of flexibility in adapting itself to the cross section of the bore, without using cord wood or other packing, the amount of which may

run high, in shattered rock, where the overbreak runs from 15 to 25 per cent. and sometimes more.

When ground pressure is high, the sets have to be spaced very close together, sometimes side by side, and in such cases, economy in material disappears altogether. Furthermore, this type of timbering is not efficient when unsymmetrical loads are thrown on it, and the rupture of one segment for instance, is enough to allow a whole set to collapse.

It becomes also necessary to leave the timbering within the masonry or concrete lining, and thus increase the width of the bore, a feature which should be avoided in heavy ground, thereby increasing the yardage of excavation by 2 to 3 yd. per lin. ft., in single-track tunnels and by 3 to 4 yd. in double-track bores. When the concrete lining is also to extend around the timbers, the yardage of the lining is also increased materially.

Timbering the St. Paul Pass Tunnel

Fig. 45*a* illustrates the type of timber lining used in connection with this bore. The timbers are 12 × 12-in. Oregon fir, the posts are 16 ft. long, the wall plates 18 ft. and have a lap joint of 12 in. fastened together with two ¾-in. bolts. The sills were 4 ft. long and the arch is made of five segments with joints slotted for a key. The usual spacing of the ribs was 4 ft. center to center, but this distance was reduced as the pressure became greater. In some places the timbering was placed without spacing between the ribs. The lagging over the arch is 4 in. thick, but on the walls where any at all was used, it varied from 4 to 2 in. The concrete lining and floor was placed at those sections of the bore where the pressure was greatest and a year after the driving was completed.

Where the pressure was great, a built up arch was substituted for the solid timber segmental rib. It sustained greater weight without distortion, was more quickly erected and did not collapse when an unusually heavy shot in the bench lowered a wall plate. It also more closely approached the true circular arc.

Timbering the Murray Hill Tunnel

The system used in this bore is illustrated by Fig. 49. A seven-segment arch set was used where the rock was seamy. After part 4, Fig. 48, had been removed, the timbers supporting

the roof of the excavation were erected. The timbering consisted of heavy frames placed transversely to the axis of the bore and supporting the lagging. At the bottom of part 4, were placed longitudinally 12 × 16-in. beams, and upon these rested the segments, which formed the set.

When the pressure was too great, the crown segment was reinforced by a 6 × 12-in. beam, kept in place by two 12 × 12-in. inclined posts resting on templates. The timber was left in the concrete lining.

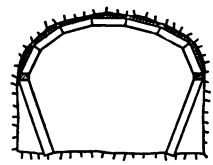


FIG. 49.—Timbering Method, Murray Hill tunnel.

Costs of Timbering Railroad Tunnels

The cost of timbering the St. Paul Pass tunnel was as follows:

Items	Cost per M. ft. B.M.	Cost per lin. ft.
Timbering delivered at Taft	$18.50	$9.25
Hauling timber, 2–½ miles	4.00	2.00
Timber framing	4.50	2.25
Cord wood	4.00	0.40
Iron	....	0.40
Erecting on bench	....	2.00
Erecting in heading	....	2.35
Total	....	$18.65

The cost of timbering a double-track tunnel on the P.C. & W.R.R. was as given below. The timber was 12 × 12-in. stuff, 4 ft. center to center with 4-in. lagging.

Item	Cost per M. ft. B.M.
Georgia pine, f.o.b. cars	$23.60
Hauling, 6 miles	3.00
Cost of framing	5.00
Cost of erecting and bracing	3.00
Total cost in place	$34.60

The cost of timbering various railroad tunnels was as follows:

Name of tunnel	Number of tracks	Cost of timbering per lin. ft.
Cascade	1	$9.40
Stampede	1	10.50
B. & O.	1	14.70
Busk	1	12.30
Kingwood	2	8.50
New Raton	1	15.00
Little Tom	1	17.00

Lining Railroad Tunnels of Moderate Length

The method of lining railroad tunnels vary according to their location, the materials available for lining purposes and the pressure to be resisted.

Stone masonry is now used less extensively on account of its high cost, especially since concrete has been adopted for lining purposes, and also since a better quality of pressed or burned bricks has been made available.

For the purpose of supporting the forms and lagging used in connection with the lining during construction, rib centers, carried on vertical posts, as shown in Fig. 50 or on travelers, Fig

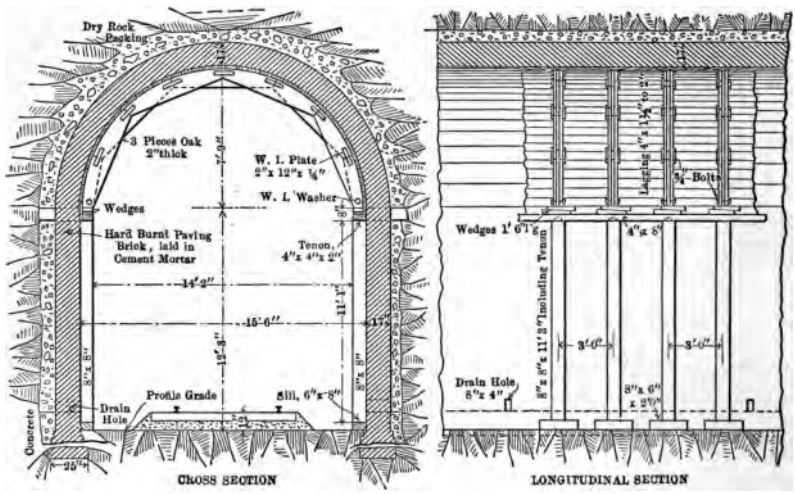


FIG. 50.—Cincinnati Southern R. R. Standard tunnel centering.

51, are used almost exclusively. The ribs are made either of timber or of structural steel shapes, such as I-beams or composite girders made up of steel angles with lacing.

Removable or collapsible steel forms of the type illustrated in Fig. 40 are used very extensively in connection with concrete linings.

Lining of the Musconetcong Tunnel

Those portions of this bore left unlined after its completion were lined in 1899 with concrete, without interruption of traffic. To facilitate the passage of trains, a concreting platform run-

ning on tracks, Fig. 51, was erected outside of the tunnel. It was first necessary to enlarge the bore, and light shots were used for this purpose, the platform being removed before a shot. It took from 15 to 20 min. to clear the tracks of débris, and thus, the traffic was not interrupted.

The side walls were built first, and then the forms were removed, and thin vertical posts were provided on which the wall plates were laid to support the iron ribs and the lagging. The ribs were made in halves, bolted together at the crown and the foot of each rested on a cast-iron sand box fitted with a screw plug.

A 16-ft. section was concreted at one time at the sides, and a

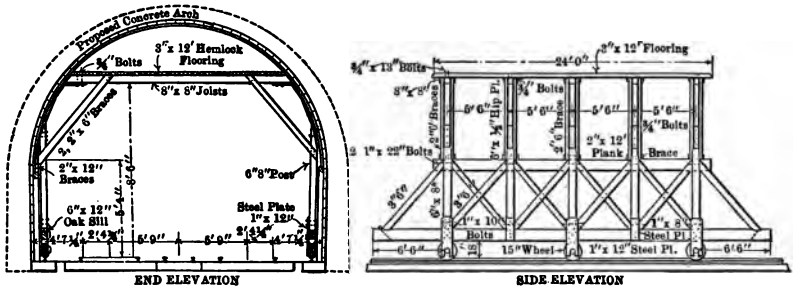


FIG. 51.—Traveling arch center, Musconetcong tunnel.

10-ft. section at the arch. As the arch concreting approached the crown, stiff struts were put in between the ribs and the roof to keep the sides from rising at the key.

Lining a Timbered Tunnel with Concrete

In the original construction of the Southern Pacific Ry. lines on the Pacific coast, all tunnels were lined with timber. At various times in recent years, it has been necessary to make extensive repairs to certain tunnels, and in the course of such repair work, standard concrete portals have been built to replace the old timber portals and a concrete barrel or lining of the new standard width constructed a certain distance into the bore. This distance depended on the nature of the ground penetrated, but it has been deemed essential to build at least 30 ft. of the concrete barrel for protection against grass fires.

A method of doing such repair work, carried on always with the usual traffic conditions is illustrated by Figs. 52*A* to 52*F*.

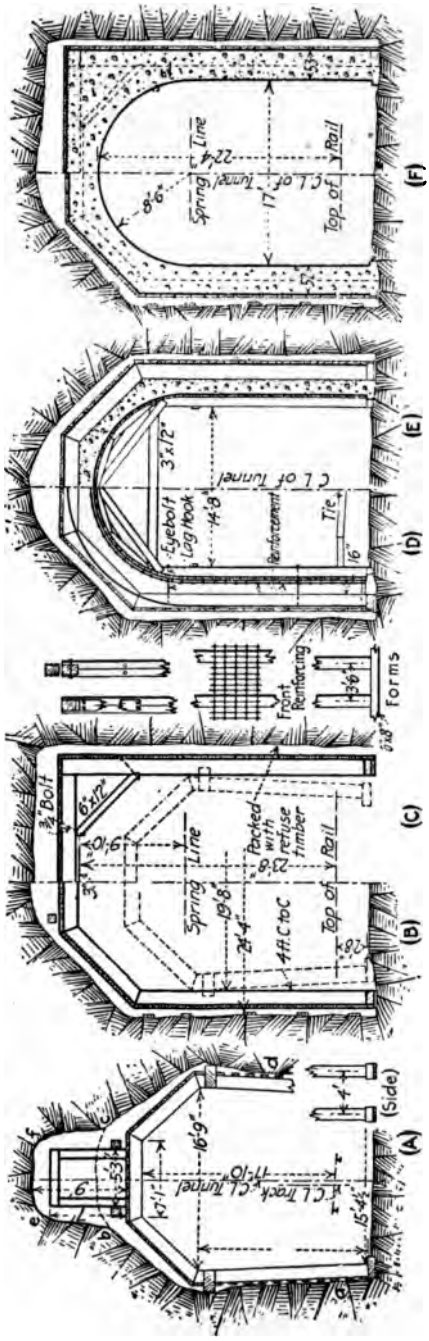


FIG. 52.—Sections showing the successive stages of work in lining an old timbered tunnel with concrete, Southern Pacific Ry.

In Fig. 52*A* is a section of the typical old-timbered tunnel (*a*, *b*, *c*, *d*). The upper part of section *A* shows the first step of the improvement work, which consisted in driving a heading or drift (*b*, *e*, *f*, *c*,) above the roof of the tunnel, the original packing being removed along with the necessary additional excavation. The material was excavated from the corners and the side walls trimmed as fast as the new timber section was advanced. It was usual to maintain the drift about 20 ft. in advance of the timbering.

Square sets were used in bad ground where greater pressure seemed to demand stronger supports. The cost of erecting the square sets was greater because of the additional labor involved in raising the long heavy cap and the double plumb post.

After having set the timbers and allowed a reasonable time to elapse for natural settlement, the concrete forms and reinforcing rods were put in place, as indicated in section *D*. Section *E*

shows the concrete in place between and around the timbers. There was no concrete placed behind the timbers, however, the space being filled with lagging and tightly packed with refuse timber.

Section *C* shows the concrete lining in place and stripped of the forms. The left half shows typical three-segment timbered sections concreted, and the right half shows the square-set design. After the forms had been removed the surface of the concrete was given a cement wash.

To remove the excavated material, small dump cars were used on a narrow gauge track laid between the main track. The concrete was hauled in buggies over a plank runway built between the rails to the point where it was to be used, and elevated to the top of forms by means of a cable operating on sheaves, the power being furnished by the same donkey engine supplying power to the concrete mixer stationed at the portal.

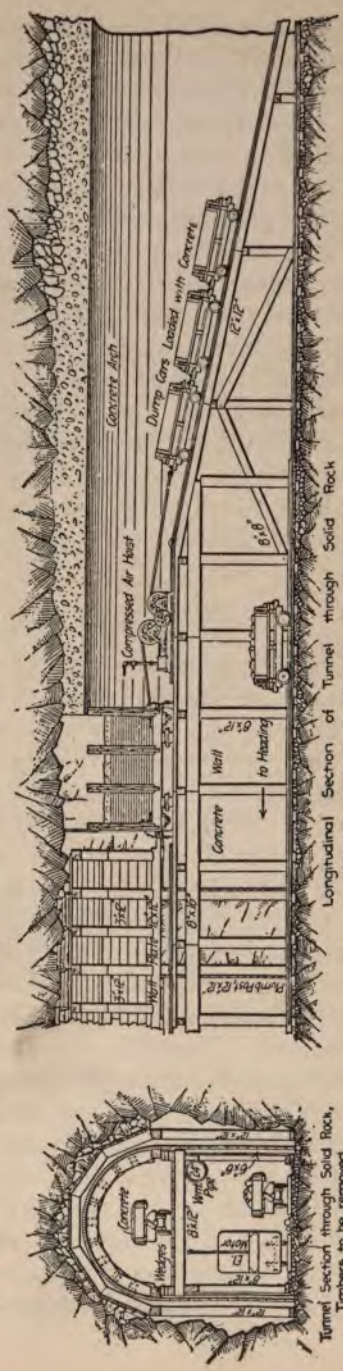


FIG. 53.—Construction method, Cascade tunnel.

Lining the Cascade Tunnel

This tunnel was lined throughout with concrete, nowhere less than 24 in. thick, only such timbering being allowed to remain as it was unsafe to move. As it was imperative that the placing of

the concrete should not in any way interfere with the driving of the tunnel, a special concreting plant was designed as shown in Fig. 53. This platform was erected in sections 500 ft. long, and it was reached by an incline up which the concrete cars were hauled by an air hoist.

While each 500 ft. of tunnel was being concreted, the advance, 500 ft. of platform was being erected with its own incline. The side walls were built in sections 8 to 12 ft. in length, the weight of the timber arch being gradually transferred from the plumb posts to the side walls. The arch sections were 12 ft. long, and plank ribs were used. As each 12 ft. was completed, the centering was advanced bodily 12 ft. on dollies and jacked up to the proper elevation. The concrete was mixed on planks installed at each portal, the proportion being 1 part cement, 3 parts sand and 5 parts broken rock. The concrete cars were hauled to the foot of the incline by electric motors. The average monthly progress of the concreting was 1115 lin. ft. of tunnel.

Lining Tunnels on the Grand Trunk Pacific

After the preliminary work of driving the Grand Trunk Pacific tunnels in British Columbia had been completed, there remained the difficult and expensive part of trimming up the tunnels and placing a permanent lining without interruption of traffic. Perhaps the most difficult work on the line was in the 1250-ft. tunnel at mile 104.5 which had to be timbered as fast as it was driven for more than 1000 ft. of its length. All this original timber had to be removed to allow the final trimming up of the bore and the placing of the concrete lining. This proved to be dangerous work because there was much loose rock behind the timbers. The method adopted was first to put in 12 × 12-in. angle braces from the side-wall posts to the tunnel floor just clear of the track. Excavation for permanent footings was then made, undermining the lower sills, while the angle braces carried the load. Concrete was then poured on foundations thus prepared and was left to harden with an offset for temporary timbering, Fig. 54.

On the offset of the permanent footings, temporary bents of 12 × 12-in. timbers were built of such size as to give sufficient clearance for trains and at the same time leave room for the lining forms. The roof timbers were then supported on these

temporary bents, while original posts, sills and wall plates were removed and the forms placed and filled up to the springing line of the arch. In some places the nature of the material was such that it was safe to remove the timbering and pour side-wall sections as long as 48 ft., at a time, while in other parts of the tunnel the ground was so heavy that 4-ft. sections were as long as could be handled with safety. After the concrete walls had set the roof timbers were removed, a section at a time. The arch was concreted by a similar process. The roof sections gave more trouble than the walls, and the length, deemed safe without timbering, varied from 3 to 42 ft.

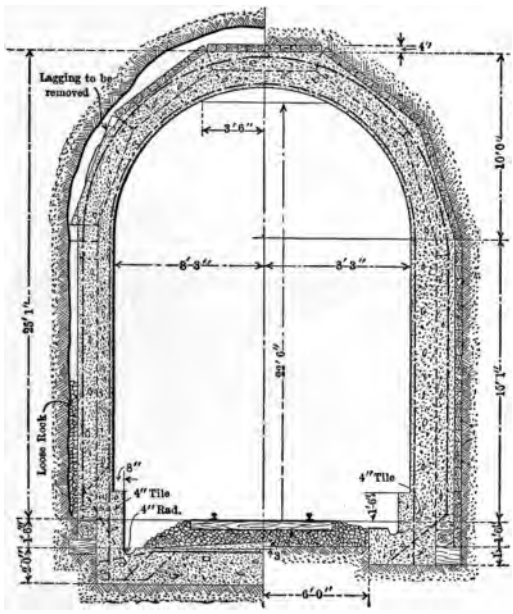


FIG. 54.—Typical half-sections of tunnel lining, Grand Trunk Pacific.

Concrete was handled in this tunnel by using a temporary platform fitted up on a standard flat car and provided with an incline up from track level. The reinforcing in the concrete lining varied with the material traversed, but a typical case in gravel and clay was given a double row of ⅞-in. round bars placed on 6-in. centers and extending from the footing on one side over the arch to the footing on the opposite side. The horizontal bars were ⅝ in. in diameter and were placed on 5-ft. centers. Where the soil

required the invert was floored with concrete, or concrete struts 4 ft. wide were placed on 15-ft. centers, as shown in Fig. 54.

Cost of Lining Railroad Tunnel of Moderate Length

The cost of lining such tunnels varies according to the materials available, the location of the bore and the wages prevailing. The cost of the concrete and brick lining of the Stampede single-track tunnel was $54 per lin. ft.

The concrete lining of the Cascade tunnel was $43.50 per lin. ft. That of the double-track Kinswood tunnel $73.

The original lining of the double-track Musconetcong tunnel costs $12 per cu. yd. and the cost of lining the portion left unlined $83.90 per lin. ft.

The concrete lining of the single-track Scranton tunnel costs $9 per cu. yd. and that of the New Raton single-track tunnel $8. The concrete lining of a 275-ft. double-track tunnel near Peekskill, with semi-elliptical roof costs $10.72 per cu. yd. The cost of relining with concrete a timbered lined tunnel was as follows:

Three-segment timbering (Fig. 52*B*)		Square set timbering (Fig. 52*C*).	
Material.....	$75.93	Material....	$88.06
Labor.....	90.02	Labor.....	107.48
Total.....	$165.95 per lin. ft.	Total.....	$195.54 per lin. ft.

CHAPTER VI

DRILLING MACHINERY USED IN CONNECTION WITH TUNNEL WORK

In tunnel work, pneumatic, electric and hydraulic drills are used now to the exclusion of steam-operated drills. The types of drill used mostly to attack the face of headings or tunnels of small cross section, are the piston and hammer drills, mounted on a vertical column or on a horizontal bar. The horizontal bar is used either independently or in connection with a drill carriage.

Electric drills have been used to a small extent in connection with the driving of several tunnels on the Catskill aqueduct, and also with that of the Jungfrau tunnel in Switzerland. The rapid development of the hammer air drill, and especially of the hammer hand air drill, that is, a one man drill, has injected a new life in modern tunnel work. In hard and brittle rocks, hammer air drills are found more advantageous than piston drill, which find a better application in softer and tougher rocks.

Air hand drills have been used successfully in driving headings of about 70 sq. ft. area, of the Hauenstein and Mont d'Or tunnels, where monthly progress of 750 and 566 ft. were attained respectively, month after month, in materials such as shales, marls, limestone, etc. In the Kandergrund tunnel, three air hand drills enabled daily progress of 15 ft. to be made in a heading of 52 sq. ft. area, driven through limestone.

In bench work of shallow depth, drills of the plugger type or jack hammers have given excellent results for down-holes. For stoping work, stopers will be found efficient in most cases, either to widen the bore or to increase its height. Plugger drills are used especially for trimming, cutting hitches, etc.

The weight of drills as used in tunnel work varies according to the type and make, the approximate weight of several types being as follows:

Piston drill, unmounted	200–350 lb.
Hammer drill	150–160 lb
Plugger drill	43– 65 lb.
Jack hammer	40 lb.
Stoper	75 lb.

Hydraulic drills possess the disadvantage of necessitating a very elaborate plant and piping system, owing to the high pressure required (about 1400 lb. per sq. in.), and their use is thereby very limited, especially in connection with tunnels of short or moderate length or of small cross section. Hydraulic drills have been used in connection with driving the headings of the Arlberg, Simplon, Albula and Tauern tunnels. Their power consumption is less than that of piston drills and about the same as that of air-hammer drills. The following table gives the type, number and mounting of drills used in connection with headings and tunnels of small cross section:

Name of tunnel	Method of mounting drill	Type of drill	Number of drills
Simplon	Carriage	Hydraulic	2–3
Albula	Carriage	Hydraulic	3
Loetschberg	Carriage	Pneumatic	4
Mont d'Or	Not mounted	Pneumatic	4
Hauenstein	Not mounted	Pneumatic	3–4
Weissenstein	Carriage	Pneumatic	3–4
Granges	Carriage	Pneumatic	4
Mount Royal	Carriage	Pneumatic	4
Tallulah Falls	Column	Pneumatic	4–5
Gunnison	Hor. bar	Pneumatic	4
Laramie Poudre	Hor. bar	Pneumatic	3
Strawberry	Vert. column	Pneumatic	2
Russell	Hor. bar	Pneumatic	1
Rawley	Hor. bar	Pneumatic	2
Jungfrau	Vert. column	Electric	2
Walkill	Vert. column	Pneumatic	4
Rondout	Vert. column	Pneumatic	4
Hunters Brook	Vert. column	Pneumatic	4
St. Louis intake	Hor. bar	Pneumatic	4

DRILL CARRIAGES

Carriages or trucks of more or less elaborate design, serving the purpose to carry drills, have been used for many years, in connection with the driving of long tunnels, beginning with the Mont Cenis tunnel.

However, no carriage has yet been put on the market that has given satisfactory results under any and all conditions of tunnel driving. The aim sought in using a drill carriage, in heading work especially, is to render easy the setting up and taking down

FIG. 55.—Ingersoll-Rand drills used for stoping down material overlying bottom heading in Lookout Mountain tunnel.

FIG. 56.—Leyner-Ingersoll drills mounted on column in heading work.

(*Facing page* 64.)

FIG. 57.—Jack hammers used in connection with shaft sinking.

FIG. 58.—Jack hammer used for trimming work in New York pressure tunnel.

of drills, also in bringing these back and forth before and after a shot.

In order to be of real practical value, a drill carriage must be of simple design and construction, and yet it should be strong enough to carry and stand the jar or reaction of four or five drills working simultaneously. Its dimensions must be reduced so as to cause little obstruction in the heading and not be a hindrance to mucking operations.

In deeply overlaid tunnels, the heading, being frequently subjected to heavy ground pressure, requires close timbering (see Fig. 80*a*), and often little room is left for the rolling stock; therefore, the drill carriage should be compact and not unnecessarily heavy.

Fig. 60 illustrates the first type of carriage used in the Loetschberg tunnel; the purpose of the tilting beam was to reach far over the muck pile, and to give the drills a broad vertical range. It was found that the tail end of the tilting beam and the counterweight were a serious hindrance to mucking; besides the carriage was subject to easy derailing, when hauled back and forth. It was subsequently replaced by the type illustrated in Fig. 61, which has given much satisfaction in connection with the driving of the Loetschberg, Mont d'Or and Granges tunnels.

This type of carriage can be used effectively only under the following conditions:

1. The heading must not have a cross-sectional area much over 80 sq. ft.
2. The height of the heading must not preferably be over 7 ft.
3. The drill holes must not be over 5 ft. deep.
4. The consumption of explosives must be high in order to break the rock into small pieces.
5. The rounds must be fired so as to throw the muck far back from the heading's face.
6. The gauge of the track for a heading up to 10 ft. wide must not be over 30 in.

Item 1 will be readily understood: when firing a round in a heading having a large cross section, the yardage of the blasted material is large and thus causes delays in bringing the drill carriage back to the heading's face.

If the heading is much over 7 ft. in height, the upper and lower holes will have too steep a slope, thus causing the rock to break irregularly and making the floor uneven.

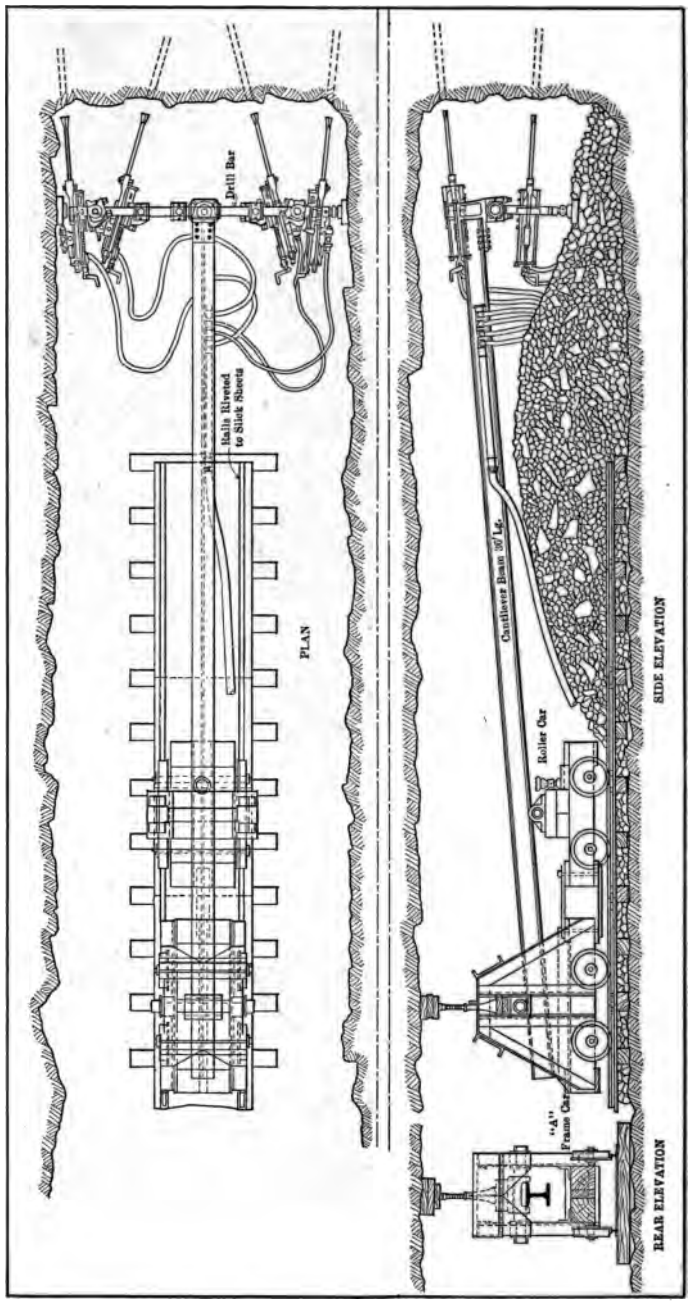


FIG. 62.—Drill carriage used in Mount Royal tunnel.

Fig. 59.—Stoper drill used in connection with driving an upraise.

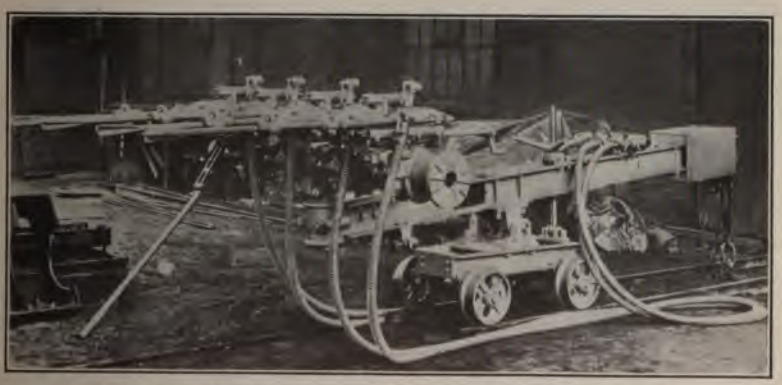


Fig. 60.—Drill carriage used first in Loetschberg tunnel.

(*Facing page* 66.)

Fig. 61.—Drill carriage used last in Loetschberg tunnel.

Fig. 63.—Drill carriage used in connection with electric drills.

If deep bore holes are used, and if the consumption of explosives is low, the rock will break in large pieces and will pile up directly in front, instead of being thrown back, of the heading's face.

The drill carriage used in the Loetschberg tunnel has enabled daily progress of 15 to 40 ft. to be made daily, according to the material penetrated and the efficiency of the mining crews. As many as eight rounds of shots were fired daily, thus enabling 65 to 80 cu. yd. of solid material to be excavated per 24 hr.

Fig. 62 illustrates the drill carriage used in driving the Mount Royal tunnel. In order to enable drills to be set up soon after a shot, a long tilting beam has been provided, reaching far over the muck pile. This beam also gives the drills a large vertical range, and thus the upper and lower drill holes can be given a very flat slope.

This carriage has given very satisfactory results under the prevailing conditions, enabling as many as 810 lin. ft. of heading to be driven in 1 month.

Fig. 63 illustrates a type of drill carriage put on the market, and to be used in connection with electric drills. Like the Loetschberg carriage, it is suitable only for headings of moderate height.

Power and Compressor Plants Used in Connection with Tunnel Driving

Compressors such as required to furnish air for drilling machinery and miscellaneous tools are usually of the straight and duplex type, driven either by steam, water or electric power, or else by internal-combustion engines.

Where coal is expensive, or when a high-head water power can be developed at a reasonable cost, compressors driven by water wheels can be used to advantage, under certain conditions. If, for instance, the tunnel, after its completion, is to be provided with a permanent ventilating plant, electric generators driven by water wheels will answer the purpose to drive fans or blowers, at a reasonable cost, in remote localities far from railroad facilities or other sources of power. Yet the largest proportion of air-compressor plants are driven by steam engines. Turbo compressors have made their appearance, and they will undoubtedly find a broad application in due time.

Combustion engines of the Diesel type have been used in Europe in connection with tunnel work, one of the first applica-

tions being that made in connection with the Hauenstein tunnel, in Switzerland.

The chief accessories used in connection with compressor plants are pre- and after-coolers, air receivers and reheaters, together with the piping system serving the purpose to convey air from the compressors to the various working points in the tunnel.

COMPRESSOR PLANTS OF VARIOUS TUNNELS

1. Tunnels of Small Cross Section

STRAWBERRY TUNNEL.—Length 19,100. Purpose: irrigation.

Two banks of transformers 22,000–2200 volts, aggregating 300 H.P.

One 427-cu. ft. air compressor, belt driven by a 125-H.P. electric motor.

GUNNISON TUNNEL.—Length 30,645 ft. Purpose: irrigation.

Eastern portal: 320-H.P. boiler capacity, in four units, air compressors having a total capacity of 2300 cu. ft. of air per min. in three units.

Western portal: 320-H.P. boiler capacity, in four units; air compressors with a total capacity of 1560 cu. ft. of air per min. in three units.

STRICKLER TUNNEL.—Length 6441 ft. Purpose: water supply.

One 220-H.P. Pelton impulse water wheel, operating under 2400-ft. head, and driving a 150-kw. three-phase generator. Air compressor driven by a 75-H.P. electric motor.

2. Tunnels of Medium Cross Section

TALLULAH FALLS TUNNEL.—Length 6666 ft. Purpose: water power.

Two 500-H.P. Francis hydraulic turbines, operating under an average head of 48 ft., driving two air compressors of 2500-cu. ft. capacity each. Owing to low-water conditions, a steam-driven compressor with a capacity of 1875 cu. ft. per min. was added, operated by two 200-H.P. Scotch marine-type boilers.

WALKILL PRESSURE TUNNEL.—Length 23,391 ft. Purpose: water supply.

Step-down transformers, 33,000–2200 volts. Two Laidlaw-Dunn-Gordon compressors of 2520-cu. ft. capacity, driven by a 500-H.P. electric motor each. Two Ingersoll-Rand compressors,

of 2600-cu. ft. capacity driven by a 500-H.P. electric motor each. One Ingersoll-Rand compressor of 1660-cu. ft. capacity, driven by a 300-H.P. motor.

ELIZABETH TUNNEL.—Length 26,860 ft. Purpose: water supply.

Two compressors of 520-cu. ft. capacity each, driven by 150-H.P. electric motors.

3. Railroad Tunnels of Moderate Length

ST. PAUL PASS TUNNEL.—Length 8750 ft.

Plant at each heading consisted of two compressors of 1205-cu. ft. capacity, 135 r.p.m., type *J2* Ingersoll-Rand, driven by two 220-H.P. 60-cycle 440-volt electric motors.

CASCADE TUNNEL.—Length 13,813 ft.

East portal: Ingersoll-Sargent duplex compressor 18 × 24 in. One Rand duplex Corliss valve compressor 20 × 36 in. One Buckeye high-speed engine 12 × 16 in., and one Chandler & Taylor high-speed engine 13 × 14. Six 150-H.P. boilers.

CANADIAN PACIFIC R. R. SPIRAL TUNNEL.—Length 3200 ft.

Three steam-driven air compressors, total capacity 3600 cu. ft. Five boilers of 100 H.P. each and four locomotive boilers of 80 H.P.

4. Long Railroad Tunnels

GRANGES TUNNEL.—Length 28,093 ft. Single track.

One transformer 15,000/500 volts. Two 2-stage Meyer air compressors, each having a capacity of 1765 cu. ft. per min. and a compression of 147 lb. per sq. in., driven by an electric motor of 500 volts, 430 amp., 40 periods. Two 4-stage Ingersoll-Rand compressors of 460-cu. ft. capacity each per min. and a compression of 1470 lb. per sq. in., driven by an electric motor. These two units to be used to load the compressed-air locomotives.

LOETSCHBERG TUNNEL.—Length 47,680 ft. Double track.

Plant on the south side: Three oil transformers 15,000/500 volts. Three 2-stage Ingersoll-Rand compressors, each having a capacity of 1950 cu. ft. per min. and a compression of 147 lb. per sq. in., driven by 400-H.P. electric motors. Also six air receivers for the above. Two 4-stage Ingersoll-Rand compressors, each having a capacity of 460 cu. ft. per min. and a compression of 1760 lb. per sq. in., driven by 250-H.P. motors, to charge the air locomotives. Also eighteen air receivers for the above.

CHAPTER VII

LONG AND DEEPLY OVERLAID TUNNELS

SINGLE-TRACK, DOUBLE-TRACK AND TWIN TUNNELS

Probably the most difficult task that confronts the engineer in tunneling is the selection of the method that will insure absolute success. Certain features having relatively little weight in connection with the projecting of short tunnels take enormous proportions when brought into relation with long tunnels, as for instance the choice between single-track and

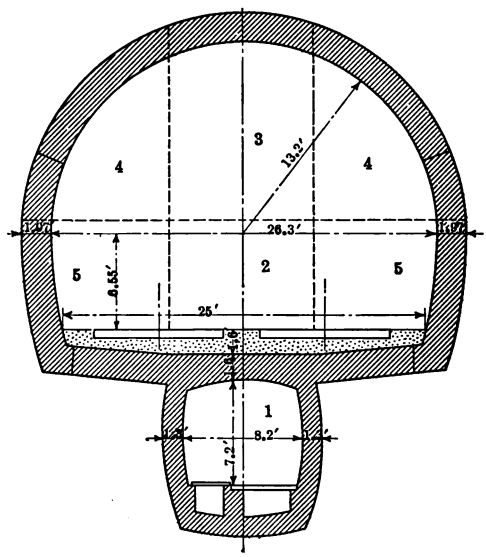


FIG. 64.—Hennings proposed double track tunnel section.

double-track tunnels. All things being equal, conditions of traffic usually dictate whether a short tunnel is to accommodate one or several tracks. This feature, however, ranks only second when a long and deep tunnel is involved; in such a case, there are factors of greater importance, as for instance ventilation during and after construction, provision to be made for handling

underground water, high rock temperature to contend with, all these introducing conditions which require due consideration at the very outset.

The St. Gothard (49,147 ft. long), Arlberg (33,600 ft.) and Loetschberg (47,680 ft.), three double-track tunnels, were pierced under the usual conditions met with in driving deep tunnels, *i.e.*, without uncommon difficulties as far as rock temperature, ground pressure and underground water are concerned, and this accounts for their successful completion.

It may be useless to point out that, at the time, it would have been impossible to drive the Simplon tunnel by a single bore of the size usually accommodating a single track, and it is very questionable whether a double-track tunnel could have been economically and successfully driven, on account of the unusual conditions encountered. In 1891, when due consideration was given the Simplon project, the idea of driving two parallel bores was brought up, in order to provide adequate ventilation during and after construction. Since the completion of the first bore of this tunnel, several authorities on the subject have expressed ideas and opinions as to proposed tunneling methods, which will here be briefly reviewed.

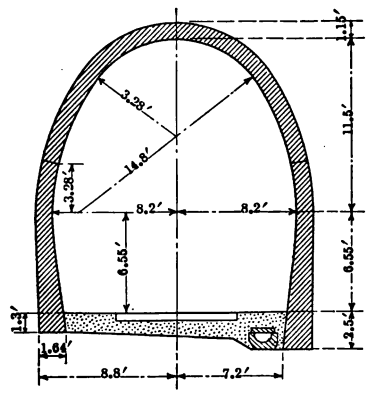


FIG. 65.—Standard section, Simplon tunnel.

For double-track tunnels, Prof. Hennings suggests the method illustrated by Fig. 64, consisting of a tunnel section accommodating two tracks, and of a bottom heading located below the main tunnel; the sequence of excavation is illustrated by numerals. The bottom heading is excavated first, and in advance of the other work; the top heading is then excavated by stoping, and the enlargement follows in successive steps. The saving effected over the cost of twin single-track tunnels of the Simplon type, Fig. 65, is claimed by Prof. Hennings to be as given in the table on page 72.

Twin tunnels would be driven on the assumption that one bore is completed first, together with a parallel heading, and that the

second bore be completed at a later date, say when the traffic conditions increase so as to require the use of two tracks.

COST OF TUNNEL PER LIN. FT.
(Without Installation)

Length of tunnel, miles	6.25	7.5	8.75	10	11.25	12.5
	$	$	$	$	$	$
1. Single-tr. tunnel No. 1 w. invert	100.0	102.5	105.0	108.0	110.5	113.5
2. Parallel heading, partly lined...	27.0	28.5	29.0	29.5	30.5	31.5
3. Transverse galleries, 1640 ft. lg.	3.0	3.0	3.0	3.0	3.0	3.0
4. Tot. cost of 1st constr. period...	130.0	134.0	137.0	140.5	144.0	148.0
5. Completion of tunnel No. 2....	78.0	80.0	82.0	85.0	87.0	89.0
6. Cost of tunnels Nos. 1 and 2...	208.0	214.0	219.0	225.5	231.0	237.0
7. Cost of double-tr. tun. w. bott. head.	176.5	181.5	186.5	191.5	196.0	201.0
8. Increase in cost (6 over 7) per cen	18.0	18.0	17.5	17.5	17.5	17.5

TOTAL COST OF TUNNELS IN MILLIONS
(Without Installations)

Length of tunnel, miles	6.25	7.5	8.75	10	11.25	12.5
1. Tunnel No. 1 and heading No. 2.	4.27	5.27	6.32	7.38	8.5	9.72
2. Completion of tunnel No. 2.....	2.56	3.13	3.78	4.43	5.1	5.83
3. Total cost of tunnels No. 1 and No. 2.	6.83	8.42	10.10	11.81	13.6	15.5
4. Double-track tun. with bott. head.	5.8	7.15	8.55	10 .05	11.6	13.2
5. Difference in cost (3 and 4).....	1.03	1.27	1.55	1.76	2.0	2.3

At a first glance, the proposition of Prof. Hennings appears to be very attractive; however, a chorus of opposing voices arose against this method, and Carl Brandau, a member of the contracting firm driving the Simplon tunnel, and well known for his connection with such undertakings, expressed his views as follows:

1. A double-track tunnel does not offer for maintenance and traffic the same advantages as twin single-track tunnels do.

2. Superimposed headings are not as advantageous as two parallel headings, during construction, as trains cannot be shifted from one heading to the other, and there is less room for materials due to the absence of transverse galleries connecting the parallel headings.

3. It is absolutely necessary to line with masonry the roof of

the bottom heading, and in most cases also the sides and invert, and these features involve costly and complicated constructions in pressure zones.

4. After the completion of the tunnel, the bottom heading becomes practically useless, and yet it is subjected to continual maintenance.

5. In general it can be safely stated that the saving of 18 per cent. over the cost of twin tunnels is but apparent, for as soon as the means of transportation during construction are no longer guaranteed, the very best driving methods become valueless.

Engr. F. Rothpletz, well known for his connection with the driving of the Simplon and Loetschberg tunnels, expressed himself as follows: Driving of very long tunnels should be carried on by means of twin bores; the distance center to center tunnels should be about 165 ft. (50 meters) and cross galleries should be provided every 1000 or 1300 ft. instead of being 600 ft. apart only.

The floor elevation of one bore should be about 1.78 ft. (0.50 meter) lower than that of the other bore.

Both bores should be completed at once, at least in pressure zones.

Driving of both headings should be carried on simultaneously. The drainage canal of the lower bore, which drains also the bore at highest elevation, through the cross galleries, should be made to follow as close to the heading's face as possible.

A. Thommen proposes to drive double-track tunnels with the use of a parallel heading located some 65 to 100 ft. distant from the main heading, and connecting with same by transverse galleries; the main heading would then be enlarged to a double-track tunnel section.

This method would of course be practicable, but costly, as the auxiliary heading together with the connecting galleries would be practically worthless after the completion of the main bore.

The method used in connection with the Loetschberg tunnel, *i.e.*, the tile partition built from floor to roof of the tunnel, for ventilation purposes, has proved very adequate and undoubtedly will do for tunnels up to 50,000 ft. long, when the overlaying depth is not excessive. Where a high rock temperature is to be expected, however, and where 1000 cu. ft. of air per sec. are required for ventilation, together with a refrigerating system, lack of space would exclude the use of this method.

Thus, it becomes evident that the size and number of bores to be adopted is by far the most important problem to deal with, as a change of method would be very costly, if not prohibitive, when the work is well under way.

Driving Methods

There are no iron rules to guide the tunnel driver in the selection of methods best adaptable to excavate long and deep tunnels. The capital invested in such undertakings requires the use of methods that will insure rapid and continuous progress together with unquestionable security for the successful completion of the tunnel, regardless of whatever difficulties may be encountered.

After the somewhat costly experience gained in driving the Mont Cenis and St. Gothard tunnels, with the top heading system and side drift method, more attention was paid to the use of bottom headings when the 33,600-ft. Arlberg tunnel was started in 1880. The unquestionable advantages gained by this method gave light to a new era in the art of tunneling, and since the completion of this tunnel the following bores have been or are being driven by the bottom heading system: Simplon, Loetschberg, Ricken, Granges, Arthur Pass, Tauern, Hauenstein, Karawanken, Wochein, Mont d'Or, Weissenstein and Wasserfluh tunnels.

When applied to the driving of long tunnels, the bottom heading, besides enabling some 50 to 65 per cent. of the tunnel section to be stoped down into the bottom heading, serves the purpose of pilot, and warns the tunnel driver against impending danger; also confirms or verifies the prediction made by the geologists, if any such have been made.

In order to obtain rapid progress, it is of the utmost necessity to spread the field of operation over as large a zone as possible, so as to eliminate, as far as practicable, all chances of interruption. As but one point can be attacked in the heading at any one time, it is given such dimensions as will give ample room for the mining operations to proceed advantageously, even under the most adverse conditions; and while its size should be reduced to a minimum, care is to be exercised that ample trackage facilities are provided, and that the sectional area of the heading will be such as not to cause the air required

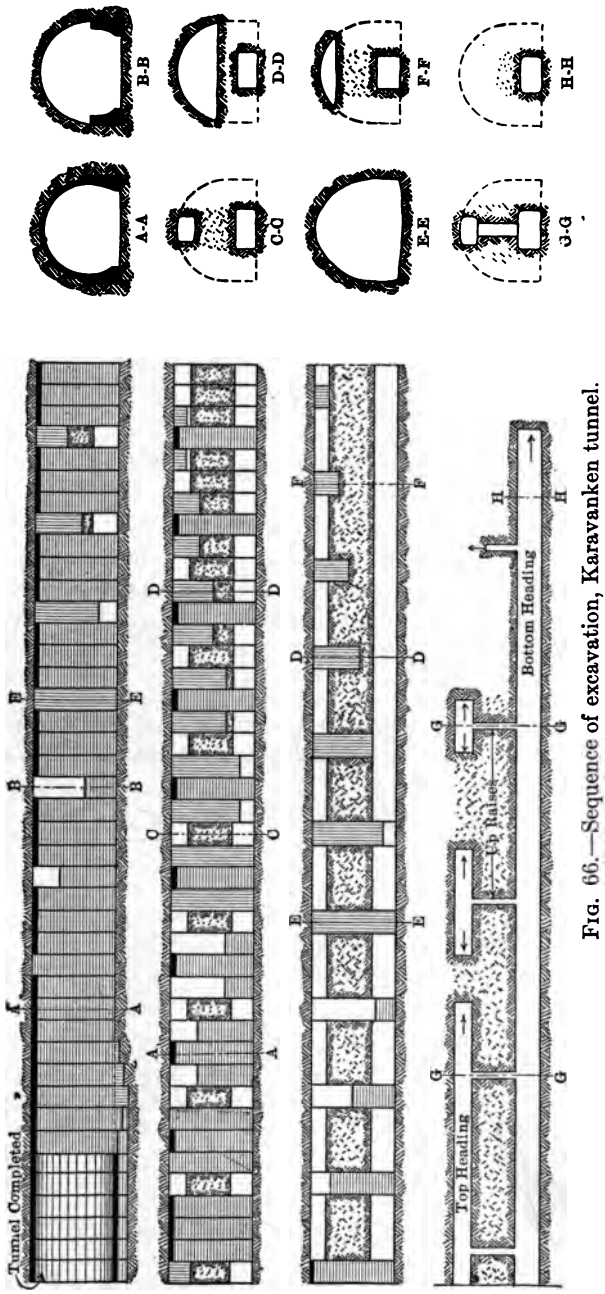


FIG. 66.—Sequence of excavation, Karavanken tunnel.

for effective ventilation to acquire too high a velocity. Experience has proven that, under normal conditions, a heading of 65 to 75 sq. ft. area can be driven, with the assistance of power drills, at a continuous daily rate of progress of 20 ft. and over, and that, without any special devices, the enlargement and lining can be made to follow the heading progress, provided the field of operation is spread so as to minimize contingencies arising from unforeseen causes.

The following tables give the monthly or quarterly progress made in several double- and single-track tunnels:

GRANGES TUNNEL, SINGLE TRACK

Year	Quarter	Excavation		Excavation		Masonry			
		Bott. heading		Enlargement		Side walls		Arch	
		North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.
1912	IV	1185	1385	935	1120	852	1050	990	1220
1913	I	2335	1150	1265	1295	905	1365	980	1380
.....	II	1165	515[1]	2045	565[1]	1375	289[1]	1375	433[1]
.....	III	1615	423[1]	975	340[1]	1365	278[1]	1345	40[1]
.....	IV	2320	1800	1945	1300	1730	1325	1590	1425
1914	I	1325	1585	2250	1125	2260	906	2240	760

SIMPLON TUNNEL, SINGLE TRACK

Year	Quarter	Excavation						Masonry	
		Bott. heading		Top heading		Enlargement			
		North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.
1902	I	1800	49	2130	813	2140	892	1525	692
"	II	1750	1100	1855	1335	1980	920	2150	735
"	III	1540	1890	1740	1090	1805	923	2190	1415
"	IV	1900	1640	1490	1000	1485	1080	1745	1040
1003	I	1515	1545	1775	1485	1625	1455	1675	1455
"	II	1625	1430	1425	2635	1205	2180	1555	2410
"	III	1715	1670	1255	1000	890	1175	1550	1370
"	IV	637	1565	855	1750	930	1735	780	1225

[1] Work hampered or partially stopped on account of inrush of water.

LOETSCHBERG TUNNEL, DOUBLE TRACK

Year	Quarter	Excavation						Masonry			
		Bott. heading		Top heading		Enlargement		Side walls		Arch	
		North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.
1909	II	2770	1400	1380	2110	1250	1515	1130	1275	1000	370
"	III	2850	1560	1835	1915	1615	1165	1560	2150	1680	2120
"	IV	1150	1420	1900	1015	2100	1650	2140	1800	1980	1950
1910	I	2250	1450	1510	770	1545	1435	1240	1525	1485	1875
"	II	2490	1500	1415	.....	1540	1910	1895	1925	1795	1985
"	III	2450	1415	1245	.....	1285	1775	1200	1770	1235	1870

HAUENSTEIN TUNNEL, DOUBLE TRACK

Year	Month	Excavation						Masonry			
		Bott. heading		Top heading		Enlargement		Side walls		Arch	
		South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.	South, ft.	North, ft.
1913	Jan.....	676	200	870	.....	755	.....	770	.....	840	.....
"	Feb.....	437	370	786	.....	385	.....	660	.....	750	.....
"	Mar....	475	745	480	180	655	.....	525	.....	610	.....
"	Apr....	733	488	512	310	853	.....	768	.....	585	.....
"	May....	940	663	532	710	420	52[1]	735	25[1]	647	36[1]
"	June....	598	922	584	880	532	157	530	105	718	90
"	July....	695	892	728	607	780	520	584	210	623	183
"	Aug.....	810	1030	572	164	650	540	788	647	532	437
"	Sept....	806	873	696	.....	820	328	597	292	710	384
"	Oct.....	787	338	682	525	662	630	760	364	618	550
"	Nov....	677	.....	775	535	520	480	565	656	740	420
"	Dec.....	700	[1]	690	560	850	630	517	577	505	460

From the above it will be readily understood that the driving progress made in the heading is not the chief object to drive long tunnels with a bottom heading, but that this method of procedure enables the enlargement, timbering and masonry lining to be carried on simultaneously, thereby reducing the time necessary to complete a bore, hence decreasing the cost of interest charges during construction, which, according to the length of the tunnel, may run from $1 to $3 per cu. yd. of material excavated.

[1] Denotes work started.

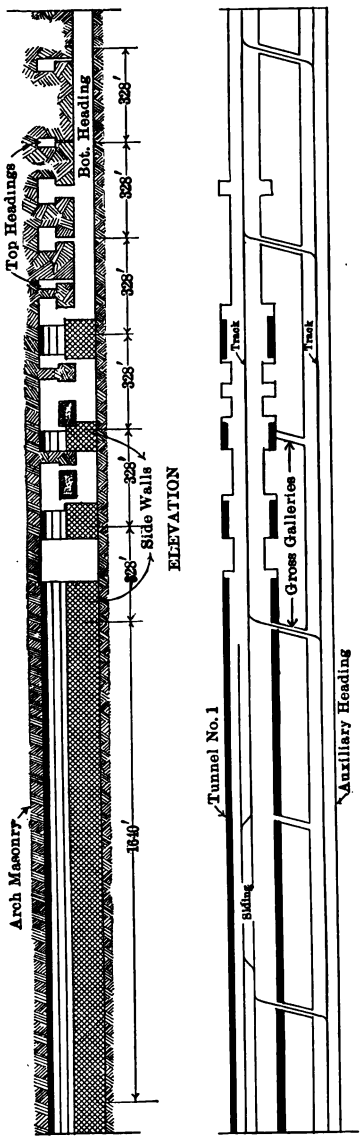


FIG. 67.—Sequence of excavation, Simplon tunnel.

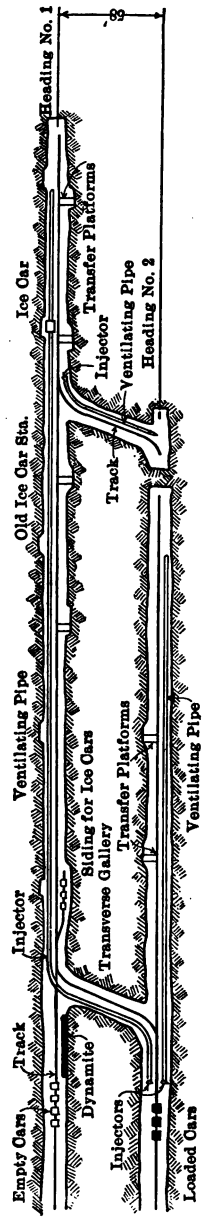
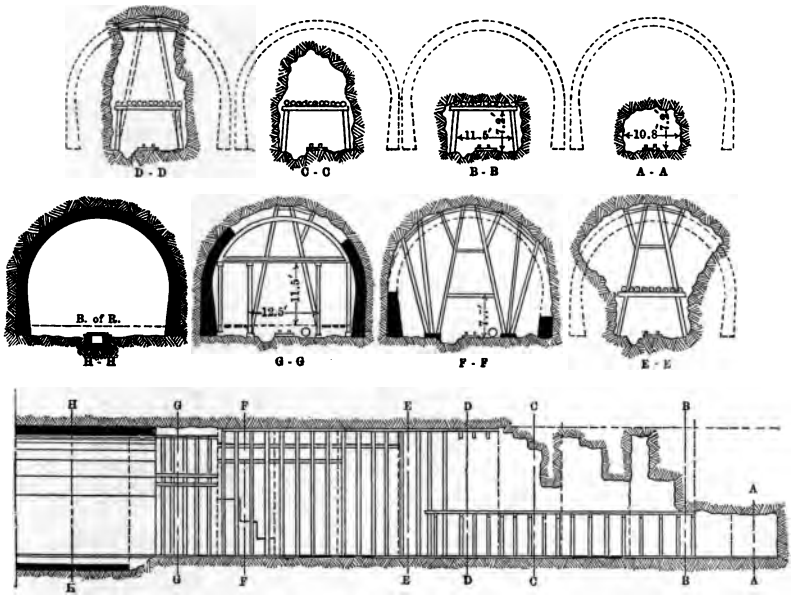


FIG. 68.—Sketch showing layout of bottom headings, Simplon tunnel

Sequence of Excavation

According to the hardness and cohesion of the rock penetrated, the sequence of excavation and the method of lining a tunnel vary greatly. In bores similar to the Karawanken and Simplon tunnels, where ground pressure plays an important part, top and bottom headings are driven first, as shown by Figs. 66, 67 and 68, and work at the enlargement and masonry proceeds in rings or working sections 20 to 30 ft. long, spaced at intervals along



A - A. Bottom Heading.
B - B Enlarging Bottom Heading.
C - C. Stoping down Roof.
D - D. Widening Roof
E - E. Excavating to Full Section.
F - F. Building up side walls.
G - G Building up Arch.
H - H. Completed section.

FIG. 69.—Sequence of excavation, Loetschberg tunnel.

the tunnel. This method is very costly, and it is resorted to only when absolutely unavoidable. This is obvious, for, instead of driving a bottom heading only, it becomes necessary to drive upraises and top headings, thus involving a large amount of drilling and blasting. Also the method of enlarging and lining a tunnel in short rings necessitates careful blasting of the adjacent unexcavated sections, hence slow work; and, in order to keep pace with the heading's progress, a large force is required. When

the rock stands well, the method used in the Loetschberg tunnel, Fig. 69, Arthur Pass, Fig. 70, and Granges tunnels is to be preferred, as 55 to 60 per cent. of the section can be stoped down into cars, thereby necessitating a minimum amount of drilling, blasting and handling. This method is by far the most economical for single-track tunnels, where the area of the heading is a large percentage of the full tunnel section.

Usually, the bottom heading is carried well in advance of the top heading or stoping stations and enlargement; for instance, on June 30, 1909, the working sections on the north side of the Loetschberg tunnel were spread as follows:

		Work completed
Excavation	Bottom heading	8,200 ft.
	Top heading	5,600 ft.
	Enlargement	5,460 ft.
	Drainage canal	4,080 ft.
Lining	Side walls	4,920 ft.
	Arch	4,560 ft.
	Drainage canal	4,080 ft.

On December 31, 1913, work at the single-track Granges tunnel stood as follows:

		Work completed
Excavation	Bottom heading	10,800 ft.
	Enlargement	8,850 ft.
	Canal	10,100 ft.
Masonry	Side walls	7,750 ft.
	Arch	7,500 ft.
	Tunnel floor	4,530 ft.
	Canal	10,100 ft.

On May 30, 1914, work at the double-track railroad Hauenstein tunnel stood as follows:

		Work completed
Excavation	Bottom heading	18,200 ft.
	Top heading	15,900 ft.
	Enlargement	15,000 ft.
Lining	Side walls	14,250 ft.
	Arch	14,000 ft.

When driving long tunnels, it becomes impossible sometimes to locate the summit of the grade half way between portals,

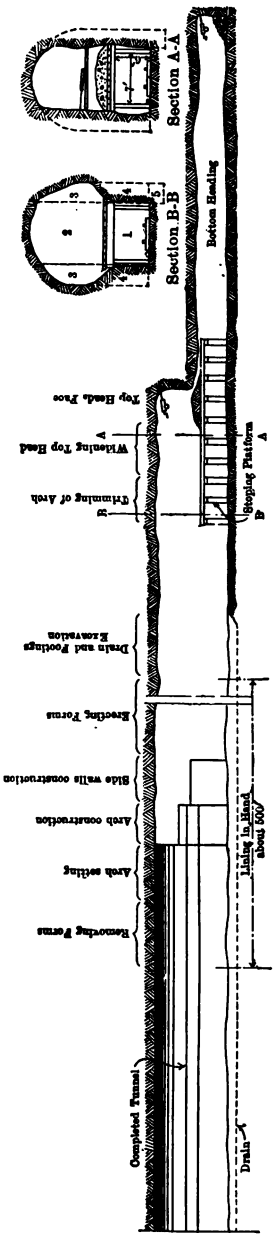


FIG. 70.—Sequence of excavation, Arthur's Pass tunnel.

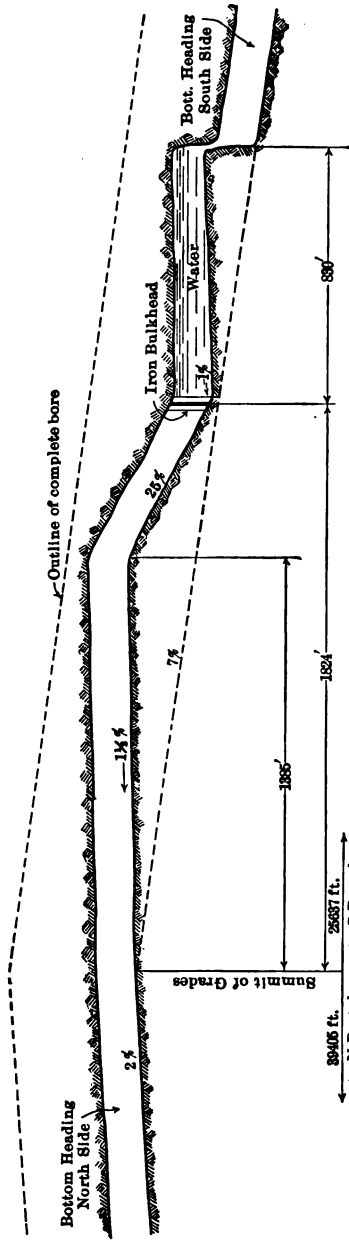


FIG. 71.—Sketch showing junction of North and South headings, Simplon tunnel.

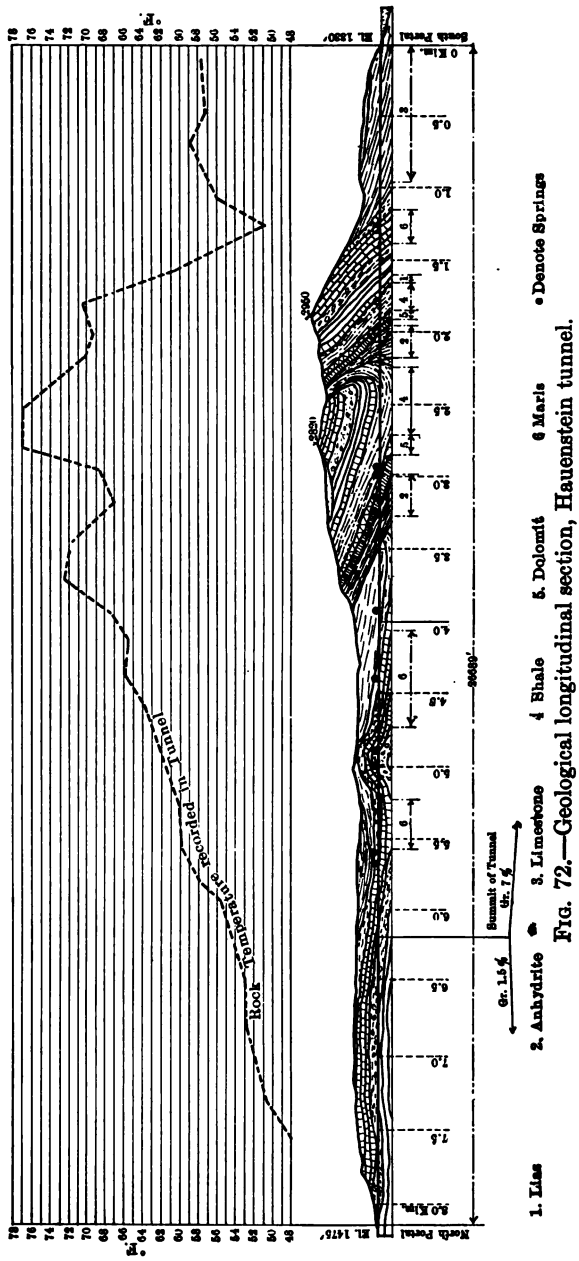


FIG. 72.—Geological longitudinal section, Hauenstein tunnel.

either on account of topographical or geological considerations, or on account of the grade necessitated by conditions of traffic. Sometimes, also, more progress is made on one side of the bore than on the other and, in order to hasten its completion, the grade is changed so as to enable driving to proceed beyond the projected summit of the tunnel.

It may occur also that more water is encountered than was anticipated during construction, and when the drainage canal becomes inadequate, the distance from the portal to the projected summit of the tunnel has to be shortened.

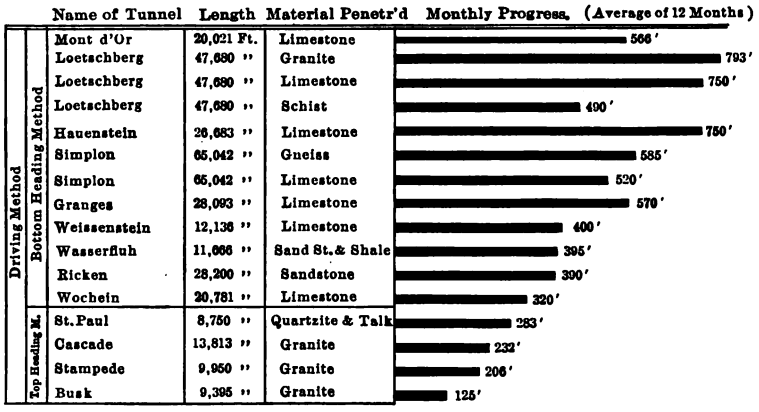


FIG. 73.—Diagram illustrating driving progress made in tunnels driven by the bottom and top heading methods.

When driving the Simplon tunnel, more difficulties were encountered on the south side than on the north side of the bore, thus affecting materially the driving progress, and the north heading was first to reach the summit of the grade, 39,405 ft. from the north portal. In order to hasten the completion of the bore, the bottom heading, at the north side, was driven on a 1-½°/00 grade, until it had reached the roof line of the proposed finished tunnel, as shown in Fig. 71. Thus, 1335 ft. were driven, without unusual difficulties; it was then decided to carry on the heading farther south, on a 25°/00 grade. An adequate pumping plant, carried on trucks, was provided to handle underground water beyond the summit of the bore, and some 489 ft. were driven, until the heading floor had reached the proposed finished tunnel floor line, on the 7°/00 grade. The heading was then

carried 830 ft. farther on a 1°/00 grade. The discharge of underground springs became such as to make pumping prohibitive, and a steel and masonry bulkhead was provided 830 ft. back of the heading's face, thus confining water, and enabling the 1824 ft. of heading driven previously to be enlarged to full section and lined with masonry.

When the crews in the south heading came near to meet the north heading, adequate precautions were taken to prevent a sudden inrush of hot water and gases.

Somewhat similar conditions prevailed during the construction of the Hauenstein tunnel, the summit of which was located 5920 and 20,763 ft. from the north and south headings respectively, as shown on Fig. 72.

CHAPTER VIII

METHOD OF HANDLING AND REMOVING EXCAVATED MATERIALS

With the exception of the material overlaying the bottom heading that is stoped down on the timber platform, the material excavated in the heading and in the side walls (see Nos. 1 and 5, Fig. 3*a*) has to be lifted onto cars.

Various devices and apparatus serving the purpose to eliminate hand mucking have been put on the market, but, generally, these have given little satisfaction and they have been abandoned. For instance, mucking machines and belt conveyors have given satisfactory results only when operated under ideal conditions, a state of affairs which seldom exists in deep tunnel work.

The chief disadvantage of most mechanical appliances serving the purpose to load or remove blasted materials, is the bulk occupied by these, and, in deep tunnels, where on account of ground pressure, heavy timbers are used, little room is left available for large pieces of apparatus.

On account of their large dimensions, steam- or air-operated shovels cannot be used in headings, and, in deep tunnels, the timbering usually prevents their use in the enlargement sections.

Small steam shovels of less than a yard capacity have given little satisfaction in tunnel work, and larger shovels cannot be operated to advantage in single-track tunnels. Even in double-track bores, their daily capacity hardly exceeds 300 cu. yd. in the average.

The following methods have been used to remove the blasted material in the heading of long tunnels: In the Simplon tunnel, cars of about 10 cu. ft. capacity were loaded after a shot, and then pushed up an inclined platform, the upper landing of which was about 3 ft. above the tunnel floor. This platform was located between the main track and the side wall of the heading. Upon reaching the top of the incline, the cars were turned around 90°, and their content was dumped onto larger cars, on the main track. This slow method of procedure was soon abandoned,

and the following method was then adopted. About 100 ft. back of the heading's face, two transfer trucks were provided; one for the drill carriage, the other for one of the two muck cars that were brought forward to the muck pile from the main siding, as shown by Fig. 74. When loaded, car "*A*" was taken back to the main siding, and car "*B*," which had been left on the transfer truck, was pushed over to the muck pile, and so on.

In the Loetschberg tunnel two cars were pushed forward from the main siding close to the muck pile (see Fig. 75). One car "*A*," was turned over on its lateral side, so as to clear the track, the other car "*B*," being loaded as rapidly as possible, by a shift of eight muckers, four of them only working simultaneously. When loaded, car "*B*" was pushed back to the main siding, while car "*A*" was thrown back on the track and loaded. This method of procedure enabled twenty-four men to remove 115 cu. yd. of solid rock per 24 hr.; according to the material handled it took from 11 to 19 min. to load and remove 1 cu. yd. of solid rock. Limestone, being lighter and broken in small pieces was handled somewhat easier than crystalline schist or granite. When driving the Kaiser Wilhelm tunnel, the method illustrated by Fig. 76 was used. About 200 to 300 ft. back of the headings face, the top and bottom headings were connected by an inclined shaft. A bridge "*E*" hinged at "*A*" and operated by a winch "*B*," enabled small cars "*C*" to be raised by power to the upper heading, and their content to be dumped into cars "*D*," in the bottom heading, through an upraise. The bridge was raised before a shot. The station was moved forward again when 1000 ft. away from the headings face.

Loading and removing the muck in the Mount Royal tunnel proceeded as follows, Fig. 77: Two cars of 40 cu. ft. capacity each were kept at the heading, and before each round was fired, they were pushed back as far as the shooting switch, so that there was no obstruction in the way of men when coming from and returning to the heading after each shot. When the last shot was fired, the cars were pushed back by the men as they went in, and were placed in position No. 1 and No. 2. Car No. 1 on spur track was loaded first, car No. 2 on main track being left back a slight distance to allow the muckers all the elbow room they could get to work in. By this time, the locomotive with two empty cars Nos. 3 and 4 comes in and couples on car No. 1, which, as soon as loaded, is run back and pushed in behind No. 2 which

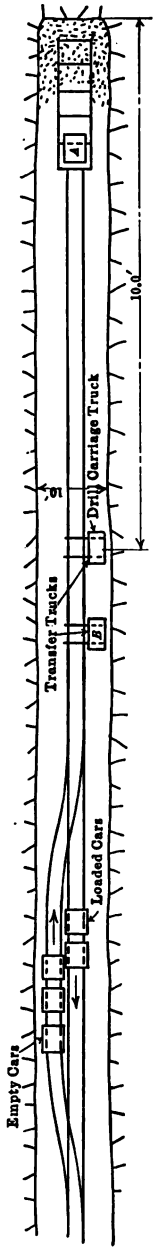


FIG. 74.—Mucking method in heading of Simplon tunnel.

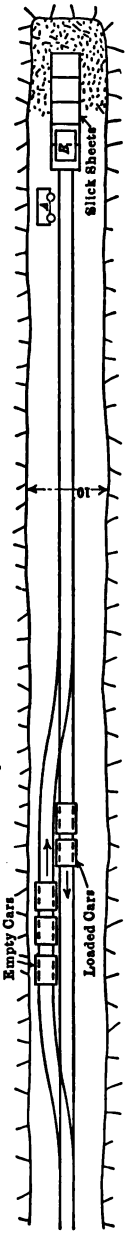


FIG. 75.—Mucking method in heading of Loetschberg tunnel.

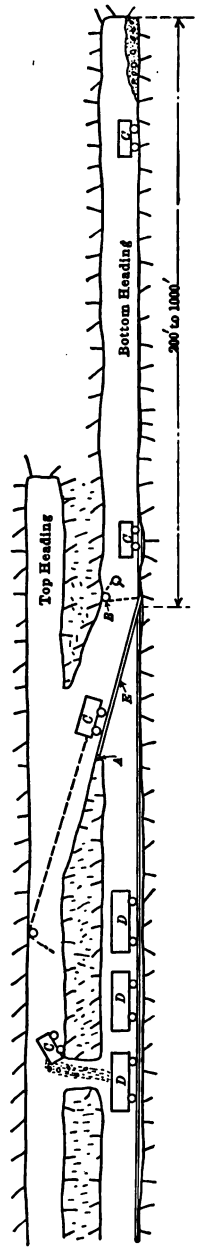


FIG. 76.—Mucking method in heading of Kaiser Wilhelm tunnel.

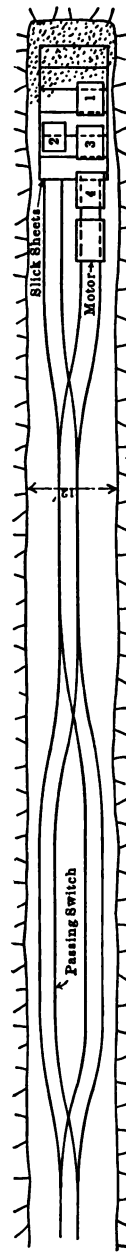


FIG. 77.—Mucking method in heading of Mount Royal tunnel.

has been pulled up to the muck as soon as No. 1 car is loaded. The locomotive then returns, empties Nos. 3 and 4 to the spur track, shifting back and picking up cars 1 and 2, now loaded, and proceeding to the tunnel's exit. The men start loading car No. 3 and a man pushes car No. 4 back and switches it on the main track to the position of No. 2, as shown in the sketch. The locomotive with two empties that have passed the loaded cars at the passing switch then comes in and repeats the operation.

HAULAGE METHODS

1. Tracks

The daily removal of some 500 to 600 cu. yd. of solid rock, that is, 800 to 900 yd. of loose material, also the haulage of 100 cu. yd. or more of masonry, together with timbering material, explosives, tools, and the transportation of tunnel crews, necessitate a very adequate train service in long tunnels, where all operations of excavation and lining are carried on simultaneously. Trains are run on a fixed schedule, modified from time to time as work proceeds, and, as trains of 40 to 50 cars are run at a speed of 8 to 12 miles per hr. adequate trackage facilities must be provided for. As the field of operation in the tunnel is spread over a large zone, it is of absolute necessity that the schedules are strictly observed so as not to cause havoc in the tunneling operations.

For instance, in addition to driving the heading, there are several stoping stations; work at the enlargement, timbering and lining is going on simultaneously at several points, each provided with a siding, so that the mileage of track laid in a long tunnef aggregates sometimes one and a half to twice the length of the bore.

The gauge of the track adopted in driving most of the long European tunnels is 30 in. A gauge of 24 in. has been found decidedly too small, and a broader gauge is unnecessary, especially in heading work. Generally, the gauge of the track is kept alike throughout the bore.

2. Cars

Owing to the fact that 60 to 70 per cent. of the material excavated is dumped onto cars from the stoping platform, *i.e.*, loaded

by gravity, the cars are subjected to considerable wear and tear, thus necessitating much repairing and replacing. The cars used for hauling blasted materials are usually plain husky wooden box cars of 30 to 40 cu. ft. capacity, the top of which is kept about 3 ft. 6 in. above the base of rail. The lateral sides are hinged at the bottom, so that, when dropping these, 50 to 60 per cent. of the material is unloaded by gravity.

The rolling equipment of the double-track Loetschberg tunnel on the north side consisted of the following material:

Steam locomotives, outside of tunnel	5
Compressed air locomotives, in tunnel	5
Box cars	384
Flat cars	21
Cars for the transportation of tunnel crews	16
Dynamite cars	2

The equipment of the single-track Granges tunnel was as follows:

Steam locomotives, outside of tunnel	3
Compressed-air locomotives, in tunnel	5
Box cars	255
Flat cars	8
Cars for the transportation of men	12

In the Granges tunnel, as many as thirteen trains were run per day with 487 cars, that is, an average of thirty-seven cars per train. In the Loetschberg tunnel there were twelve trains per day, with forty cars per train.

3. Locomotives

In the early stages of tunnel driving, steam locomotives were used for haulage purposes, but the increasing train capacity soon made their use prohibitive, although in the Simplon tunnel, specially designed engines were used quite extensively (Fig. 78). After raising the steam pressure up to 220 lb. per sq. in. firing was stopped, and the locomotive was run until the pressure had dropped down to less than 100 lb.

Steam locomotives were used also in the St. Gothard, Tauern and Bosruck tunnels.

Compressed-air, electric and gasolene locomotives have now superceded almost entirely steam locomotives in connection with driving long tunnels.

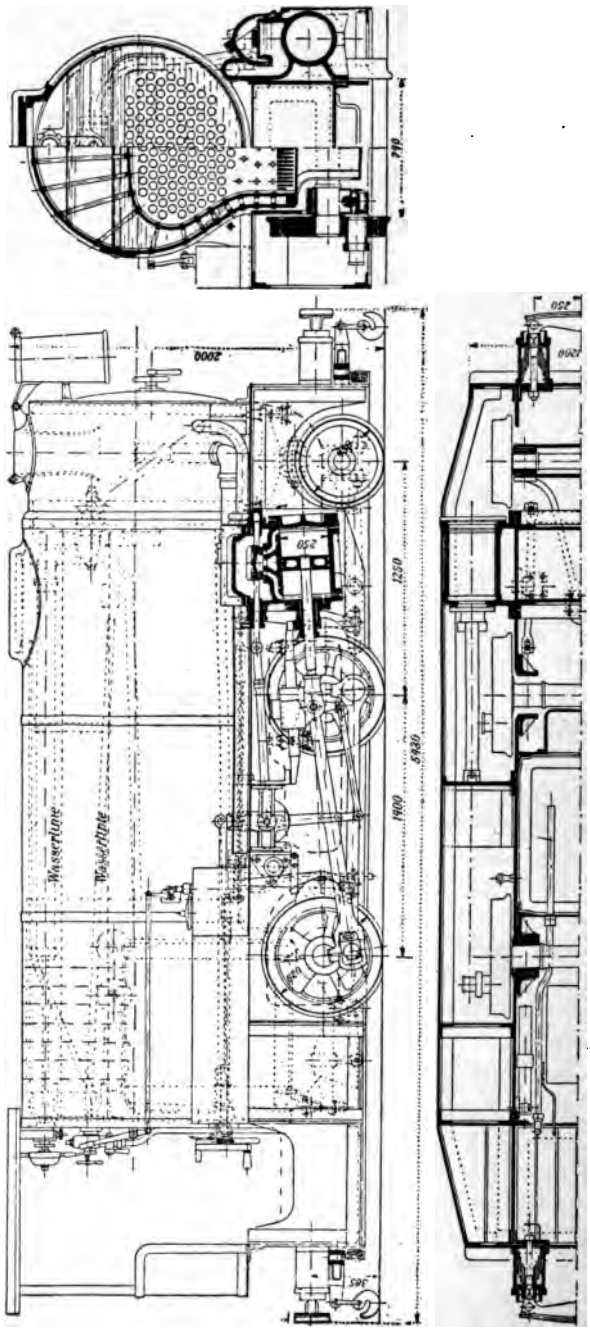


FIG. 78.—Details of steam locomotive used in the Simplon tunnel.

Compressed-air locomotives are used quite extensively, and for very long tunnels, of say, 40,000 ft. and over, this type of tractive power will undoubtedly find continued use, for, in addition to generating little or no heat, the air exhausted by the cylinders adds to the ventilation. One chief disadvantage, which makes their use prohibitive when driving shorter tunnels, is the high cost of the installations, piping, compressors, etc.

The air locomotives used in the Simplon tunnel (Fig. 79) had a reservoir capacity of 70 cu. ft. The reservoir consisted of Mannesmann tubes filled with air at 1030 lb. pressure; when passing into the cylinders, the pressure was reduced to 150 lb. per sq. in.

The locomotives used in the Loetschberg tunnel had a larger capacity; they were loaded by two 4-stage electric-driven Ingersoll-Rand compressors having a capacity of 460 cu. ft. of air per min., and a compression of 1750 lb. per sq. in.

The air locomotives used in the Granges tunnel were fed by one Ingersoll Rand electric-driven compressor, having a capacity of 460 cu. ft. per min. at 1500 lb. pressure. Air locomotives have been used also in the Hauenstein tunnel, south side, while benzene engines were used on the north side.

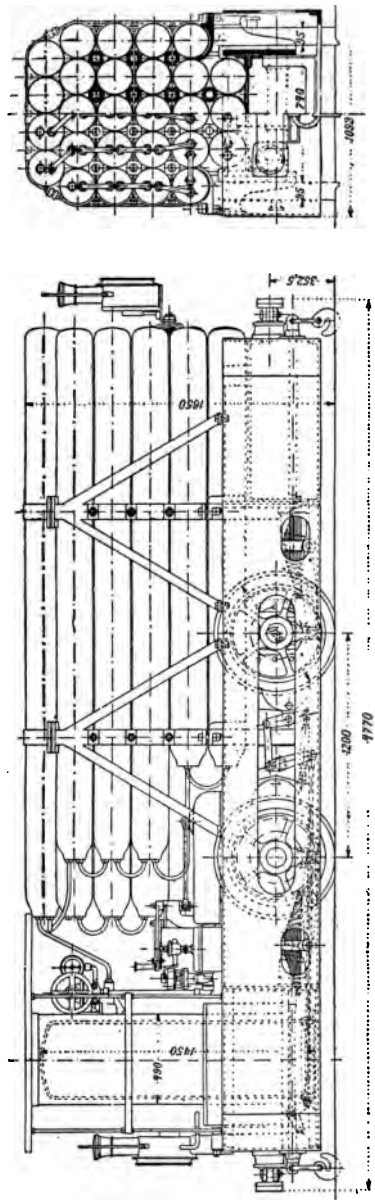


FIG. 79.—Details of compressed-air locomotive used in Simplon tunnel.

Benzene and gasolene locomotives are being used also quite extensively, and when run properly, they give satisfactory results. Their use in tunnels of moderate length is likely to become extensive, especially in the bottom heading, where electric wiring is rather an inconvenience.

Gasolene or benzene locomotives have been used in the Tauern, Bosruck and Arthur Pass tunnels.

Electric locomotives are becoming very popular in tunnel and mine work, although in tunnels driven with a bottom heading some difficulty is experienced with the overhead wiring, on account of the frequent removing of the stoping platforms and temporary timbering.

Electric locomotives have been used in connection with the driving of the Arthur Pass, Tauern and Mount Royal tunnels.

WORKING FORCE

Since the introduction of hand air drills and the adaptation of concrete blocks for tunnel lining, the force of men employed in driving long tunnels has been materially reduced as compared with the amount of work accomplished.

The working force of the Simplon tunnel had the reputation of being large; this was due chiefly to the fact that work proceeded simultaneously in two bores as well as in the cross galleries, and because excepting air drills used in the bottom heading, drilling in the remaining sections was done by hand altogether.

	Engineers, inspectors	Drillers, helpers, masons, mechanics	Muckers, com. labor	Total
Bottom heading	3	21	25	49
Enlargement	9	217	134	360
Masonry	2	37	63	102
Drainage canal	.....	6	7	13
Miscellaneous	12	34	49	95
Total	26	315	278	619

The masonry lining was made also very thick, thus requiring a large crew of masons and helpers, besides complicating the hauling operations. As tunneling methods have improved

greatly, during the past 10 years, the mining methods used in driving the first bore of the Simplon tunnel have become somewhat obsolete. For instance in double-track tunnels, twenty to thirty-five hand air drills are used for the enlargement work, thus increasing materially the drilling capacity of the mining crews. The previous table gives the average number of men employed, in the single-track Granges tunnel, per 24 hr.

Number of men employed per 24 hr. in the Loetschberg tunnel (double track).

	Engineers, inspectors	Drillers, helpers, masons, mechanics	Muckers, com. labor	Total
Bottom heading.....	3	20	26	49
Enlargement bottom heading.	3	38	20	61
Top heading.....	2	12	17	31
Enlargement.....	8	266	173	447
Canal.....	1	16	11	28
Masonry.....	4	68	125	197
Miscellaneous.....	13	78	80	171
Total.....	34	498	452	984

The three 8-hr. shift system per day has been established throughout, work proceeding also on Sundays. Holidays are observed usually, advantage being taken by the engineering force to do all precise surveys in connection with the alignment and grade of the tunnel.

CHAPTER IX

TUNNEL TIMBERING

The practice followed in timbering long and deeply overlaid tunnels, is the evolution of a system that long answered the need of the miner before it was used at all in connection with the driving of railroad tunnels.

The experience gained as to the intensity and distribution of ground pressure on the timbering of tunnels, a decidedly better knowledge of the behavior of materials used for construction purposes, and the increased cost of labor, have created a special type of timbering which meets numerous needs, such as economy in material, flexibility in erection and removal, ease in replacing

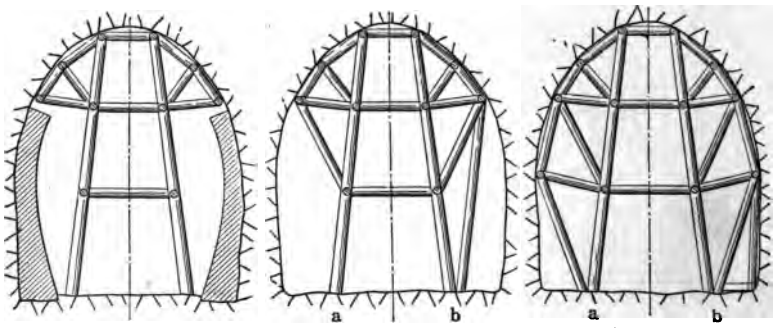


FIG. 80. FIG. 81. FIG. 82.

FIGS. 80–82.—Timbering method for single track tunnels.

overstressed or crushed members, adaptability to irregular tunnel sections without using a large amount of cord wood or other packing, and the giving of ample clearance for driving purposes.

Figs. 80 to 89 illustrate the type of timbering adopted generally with some variations in the layout of secondary members or the addition of horizontal struts. Briefly, the following principles are followed in designing and proportioning this type of timbering: All main members are in direct compression, bending stresses being avoided whenever possible, if not entirely. The length of members is reduced to frequent bracing as a pre-

caution against flexure. The details of joints and abutting surfaces are made very simple, thus avoiding the use of expensive labor. The system is complete in itself, being adapted to resist roof, floor and side pressure. This last feature is a vital point in deep tunnel work, where large overlaying masses are often set in motion during construction and where it is of absolute necessity to minimize possible disturbances, thus avoiding throwing heavy loads on the timbering and later on the lining. For these reasons, the masonry is made to follow closely the timbering, and, as all operations of construction are carried on simultaneously, the duty of carrying heavy loads is not imposed on the timbering for any great length of time; the timbering is thereby protected against deformation and decay and can be used over again with little waste and cost of framing.

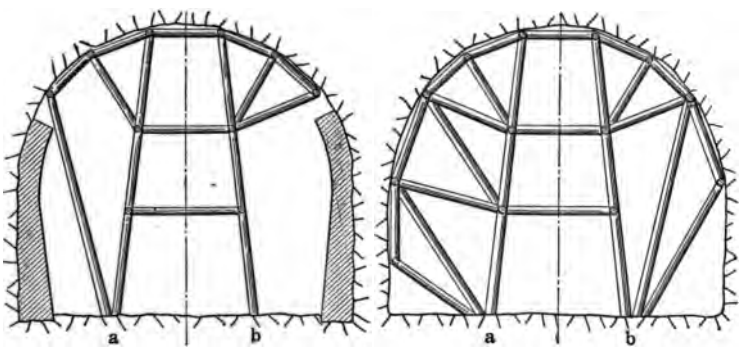


FIG. 83. FIG. 84.

FIGS. 83–84.—Timbering method for double track tunnels.

Fig. 80 illustrates the simplest form of timbering used to carry tunnel roof loads; the main vertical posts are erected first, followed by secondary members. With an increase of roof load, additional struts and braces are inserted, as illustrated by Fig. 81. Where side pressure occurs, the system shown by Figs. 82 and 84 is used. Figs. 84, 88 and 89 illustrate systems commonly used in timbering double-track tunnels subjected to heavy roof pressure.

As lining with masonry progresses, beginning with the side walls, one member after another is taken out, without thereby causing the whole system to collapse, as for instance is the case with the segmental arch rib system. The reactions of the roof

and side walls are transmitted to the floor, thereby checking, if not preventing, uplifting of the floor.

As the temporary timbering is used for construction purposes only, the members can be made somewhat lighter than for permanent timbering, so that, contrary to opinions prevailing, the

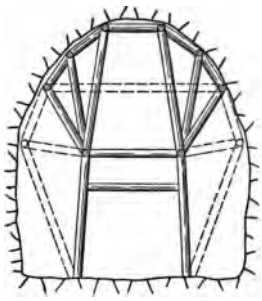


FIG. 85.—Timbering method, Ricken tunnel.

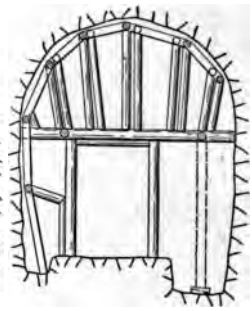


FIG. 86.—Timbering method, Arthur Pass tunnel.

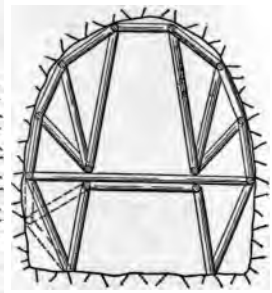


FIG. 87.—Timbering method, Simplon tunnel.

amount of timber is no more per running foot than with other methods of timbering. According to the pressure, or load to be carried, the timber sets are spaced from 5 to 10 ft. apart. Although the cost of erection and framing round timbers is in some

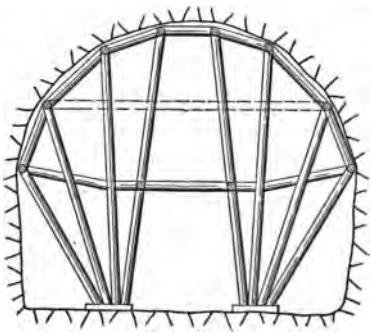


FIG. 88.

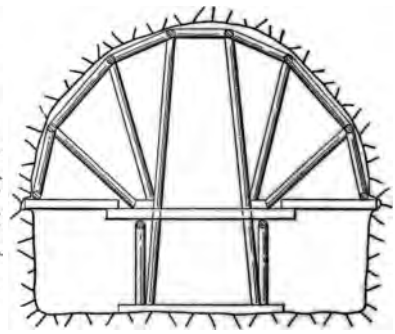


FIG. 89.

FIGS. 88–89.—Timbering method for double track tunnels.

instance higher than that of dressed timber, the cost of material is usually so much lower that it presents advantages in the case of timbering long tunnels.

One chief disadvantage for this type of timbering is that steam- or air-operated shovels cannot be used for excavation purposes,

FIG. 89*a*.—Heavy timbering in bottom heading of Weissenstein tunnel.

FIG. 89*b*.—Timbering used in Loetschberg tunnel.

(*Facing page* 96.)

Fig. 90.—Typical timbering, Mount Royal tunnel.

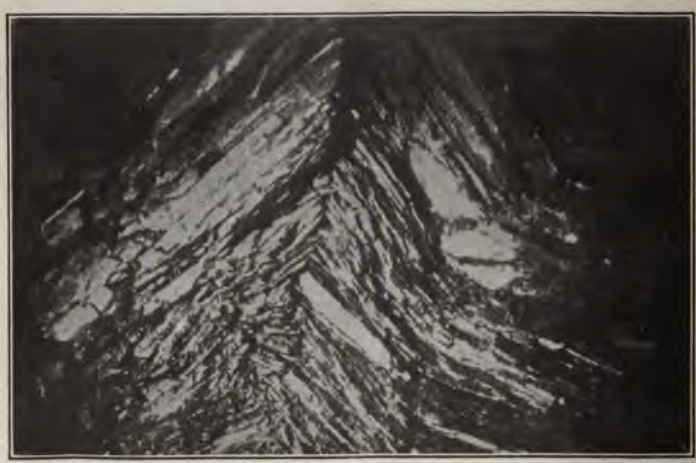


Fig. 92.—Uplift of tunnel floor, 22,100 ft. from south portal, Simplon tunnel.

owing to lack of room. This inconvenience has made the segmental arch timbering system very popular in this country to drive short tunnels, but this system is not adaptable for deep tunnel work on account of its inability to resist high or excentric and side rock pressure. Furthermore, it is hardly possible to take out any one of the segments without causing the whole system to collapse, and this has led to the practice of leaving the timber within the concrete lining, a practice, which, as referred to in another part of this book, is not favored by modern tunnel builders.

Owing to numerous conditions under which a tunnel is driven, it is very difficult to establish accurate and conclusive comparisons of cost; however, experience has proven that permanently timber-lined tunnels are costly, both from a standpoint of construction and maintenance, and improvement in tunnel work of some magnitude should lend toward leaving out altogether timber within or for tunnel lining.

GROUND PRESSURE

This subject has caused much ink to flow during the past 30 years, and yet, after numerous observations made in mines, shafts, tunnels of all kinds, as well as in laboratories, no conclusion has yet been reached that has stood unquestioned for any great length of time. The chief difficulty in designing tunnel linings lies in the lack of knowledge as to the intensity and direction of the rock pressure to be guarded against. In almost every tunnel, the geological formation and stratification vary, and often after exhaustive studies of the geological formation of a range have been made, uncertainty exists as to the behavior of the materials to be penetrated. Numerous are the failures of tunnel linings, either due to excessive and unequally distributed pressure, or to not taking care sufficiently in the designing.

The opinion of geologists and engineers, as to rock pressure in tunnel construction, vary greatly; Culmann's theory is based on the supposition that the ground pressure on a tunnel lining is greatest at the roof of the tunnel, and that the intensity of pressure depends on the overlaying depth and cohesion of the rock.

Ritter's theory is opposed to that of Culmann's, his contention

being that the pressure on the roof of a tunnel does not depend on the overlaying depth, but is equal to the weight of a body of material having the form of a semi-parabola, less the stress required to cause rupture by tension along the semi-perimeter of the parabola. The intensity of the pressure would then be independent of the depth overlaying the tunnel, but would vary according to the width of the excavation.

Heim's studies are perhaps more elaborate and cover a broader field than any others ever made on this subject. His theory, however, met with little enthusiasm, especially on the part of tunnel drivers, who will not accept the theory that the ground pressure on the roof, side walls and floor of a tunnel act as hydrostatic pressure does on a submerged body, yet with the difference that ground pressure acts more or less slowly on account of the variation in cohesion and friction of the materials caused by the unequal geological formation of mountain ranges.

According to his theory, the lining of the St. Gothard tunnel, with 5000 ft. overlaying depth, would require a lining having a thickness of 20 ft., a supposition which, of course, would make the driving of deep tunnels prohibitive. However, Heim's conception of ground pressure is far from being erroneous. Observations made in the unlined auxiliary bore as well as in the transverse galleries of the Simplon tunnel indicate that, several years after construction, excessive pressure caused the side walls, invert and roof of same to crush, thus practically filling certain sections of the bore referred to above. It has been observed that the intensity of the shelling of the rock increased with the overlaying depth. For instance, vertically stratified gneiss with 2300 ft. burden, would not show any sign of disturbance, yet, shelling of the same rock would take place with 4000 ft. overlaying depth.

Shelling of the rock took place in the Leggistein tunnel several years after its completion and similar signs have been recorded on the roof, side walls and invert of tunnels driven through apparently solid rock, usually not affected by weathering, gases, heat, etc. It is therefore possible that, in certain instances, the overlaying depth or rather weight, may cause serious disturbances in a tunnel, after, if not during construction.

It has been observed that in moderately overlaid tunnels, signs of pressure or deformation occurred first in the roof; in

deeply overlaid bores, in the side walls first and then in the roof and floor, although such phenomena have occurred in a reversed order, due to the peculiar stratification or formation of the ground, and also the crushing strength of the materials penetrated. In relatively soft materials, deformation would appear under the form of crushing or bending of the tunnel roof, floor or side walls, as shown by Figs. 91 and 92, while in hard and brittle materials flaking or shelling of the rock would take place.

EXAMPLES OF HEAVY GROUND PRESSURE

1. Ricken Tunnel

The contractors of the Ricken tunnel, Fig. 93, driven chiefly through shale and sandstone, met with much difficulty during construction of this tunnel. The ignition of coal gas was a serious hindrance to progress, and soon after its completion serious movements occurred in several sections of the side walls, in some instances decreasing the width of the tunnel by 1–½ ft., and necessitating the complete reconstruction of the masonry. In another instance, the concrete invert was raised, yielding under the rock pressure and it had to be replaced by stone masonry, over a length of 470 ft. The cost of repairs to the masonry, supplementary drainage

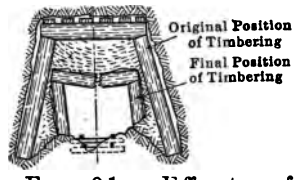


FIG. 91.—Effects of ground pressure on timbering, Karawanken tunnel.

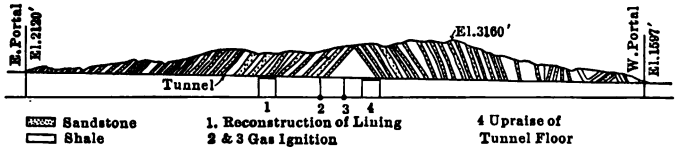


FIG. 93.—Longitudinal geological section. Ricken tunnel, 28,200 ft. long.

system, interest charges increased by delays, etc., amounted to approximately $194,000, and the opening of the tunnel to traffic was retarded fully 2 years.

2. Weissenstein Tunnel

This tunnel, Fig. 94, driven chiefly through limestone and sandstone, was lined over 87 per cent. of its length. Movements of the side walls, varying from 1 to 3 in., took place

soon after construction, and continued during 3 years, as shown by Fig. 95; it was found necessary to build concrete inverts in different sections of the bore, without interruption of traffic.

3. Simplon Tunnel

The difficulties due to rock pressure encountered in driving the Simplon tunnel, Fig. 96, hardly compare with those met with

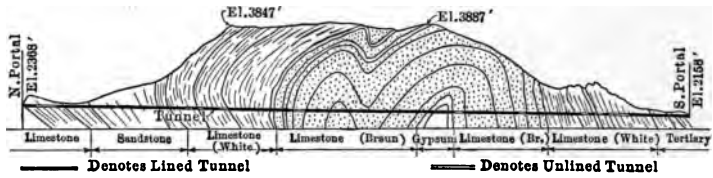


FIG. 94.—Longitudinal geological section, Weissenstein tunnel, 12,136 ft. long.

the driving of the tunnels above referred to. At a distance of 14,600 ft. from the south portal, with some 4000 ft. of overlaying gneiss having a schistose appearance, the ground pressure necessitated a masonry lining 5.5. ft. thick, over a length of 138 ft. at a cost of $1520 per lin. ft.

4. Bosruck Tunnel

Driving of the Bosruck tunnel proceeded without difficulty between kilometer 0.9 and 1.0 and the timbering was made very

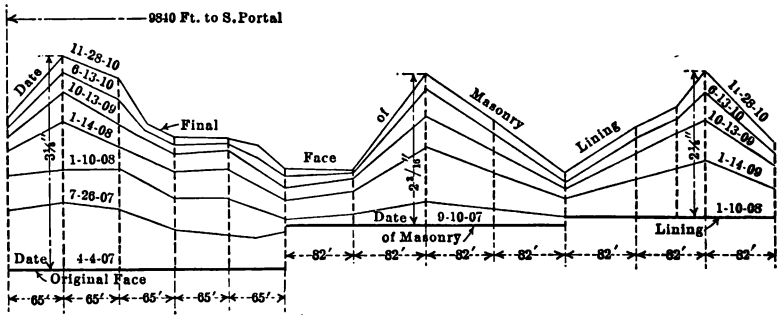


FIG. 95.—Diagram illustrating movements of side walls, Weissenstein tunnel.

light. The overlaying depth was about 1600 ft. Although the material penetrated was soft, no sign of pressure was noticeable, and therefore, the masonry lining was given a thickness of only

21.6 in., at the arch crown. One year later signs of weakness developed, and it was found necessary to rebuild the lining.

5. Karawanken Tunnel

On account of fire damp which collected at high points in the tunnel, the top heading in the pressure zones was driven independently of the bottom heading. Already before work had been started on excavating the bore to its full section, it was found that the layer of rock between the top and bottom headings did not furnish sufficient support, and in some instances the rock gave way in such a manner that the floor rose in the top heading, while in the bottom heading the roof came down, and thus great difficulty was experienced in lining the bore. The pressure zone extended over a length of some 6300 ft., and the lining had to be rebuilt over a length of 1150 ft., although, where the pressure was a maximum, ashlar masonry had been used. In some instances, the masonry lining began to move while it was being

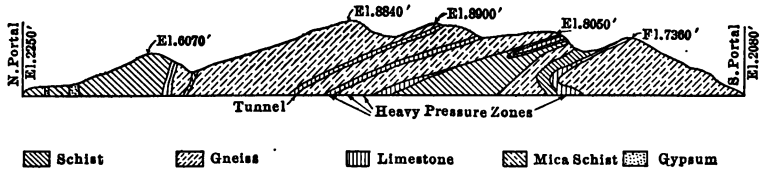


FIG. 96.—Longitudinal geological section. Simplon tunnel, 65,042 ft. long.

built already; the side walls were lifted as much as 10 in. and they moved horizontally at a rate of $\frac{3}{32}$ in. in 24 hr.

Illustration of Ground Pressure Acting on a Tunnel Lining

It has been observed that, when a cave-in occurred in an earth or rock tunnel, or when a sand or rock bin, or a silo filled with grain was being emptied from the bottom, the void resulting from the cave-in, or from the material extracted, would take a vaulted shape, nearing that of a parabola. The height of the vaulted space was found, in some instances to be independent of the depth or weight of the overlaying material, but, on the other hand, was dependent on the width of the excavation and of the cohesion of the material under consideration. Let A, B, C, D, Fig. 97, represent the section of a deeply overlaid tunnel,

and let w, x, y, z, be the weight of the overlaying mass, acting at say, roof elevation of the bore. The material penetrated is assumed to be hard and solid, stratified horizontally in "a" and unstratified in "b." It is evident that, the load acting on the roof of the tunnel has to be transmitted to the floor, through the side walls A-C and B-D. If these are strong enough to resist the additional load or reaction of the roof load, the stress thus borne can be illustrated by the diagram s, t, r, u,

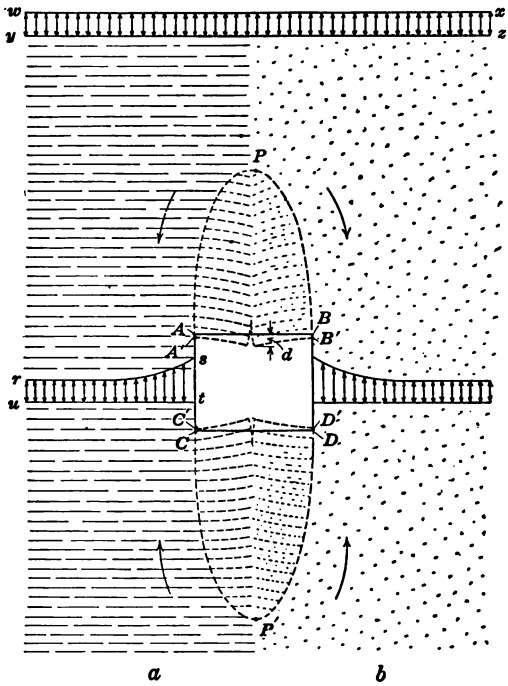


FIG. 97.—Diagram illustrating the distribution of ground pressure in a deeply overlaid tunnel having hard and solid side walls.

the stress reaching a maximum value at the side walls, and decreasing in intensity at a distance away from same, down to a point where r-u has a value equal to w-y.

Under repeated blasting, and if the strength of the material penetrated is such as to allow a vertical movement of the roof and floor, the roof line will move down to A'-B', and as action and reaction are equal, the same process will be undergone by the floor line C-D, to a less extent, however, as the pressure is somewhat counteracted by the weight of the material underlaying

the floor. A vertical movement having taken place, it is obvious that voids have been created between the adjacent imaginary layers of rock above or below the roof and floor lines, and unless due provision is made to prevent further movements of the strata, the bore is liable to fill up, in the course of years, if not immediately. If, on the other hand, adequate timbering or lining is provided, further movement of the ground will be checked, and equilibrium will take place, as the voids caused by the initial

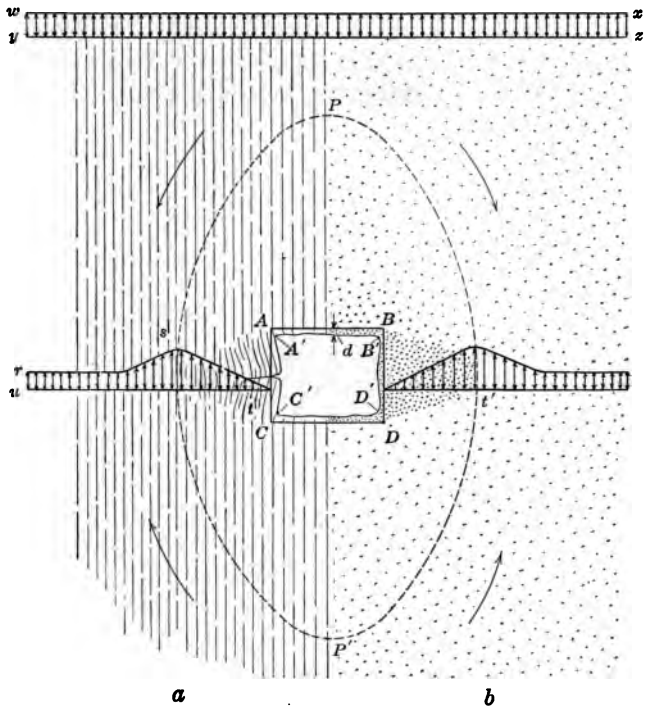


FIG. 98.—Diagram illustrating the distribution of ground pressure in a deeply overlaid tunnel having yielding side walls.

movement will fill up, due to successive settlements or swelling of the overlaying material.

Under normal conditions, the disturbed zone will be confined within an area limited by a parabola, and the load carried by the roof of the tunnel will be that due to the weight of the materials confined within *A'-P-B'*.

Now let *A-B-C-D*, Fig. 98, represent the section of a tunnel driven through yielding material, stratified vertically in "*a*"

and unstratified in "*b*." On account of the low crushing strength of the rock penetrated, and the inability of the side walls *A-C* and *B-D* to transmit to the floor the reaction of the roof load, vertical movements of the roof and floor and horizontal movements of the side walls are bound to take place. The zone of disturbance will thus be spread over a large area surrounding the tunnel, and the stress in the side wall *A-C*, for instance, can be illustrated by the diagram *t-s-r-u*. It is evident that the long axis of the parabola *t-P-t'-P'* can assume different positions, according to the inclination of the strata, but whatever position the axis may assume, the load to be carried by the tunnel lining, in deeply overlaid tunnels will always be a small fraction of the overlaying depth.

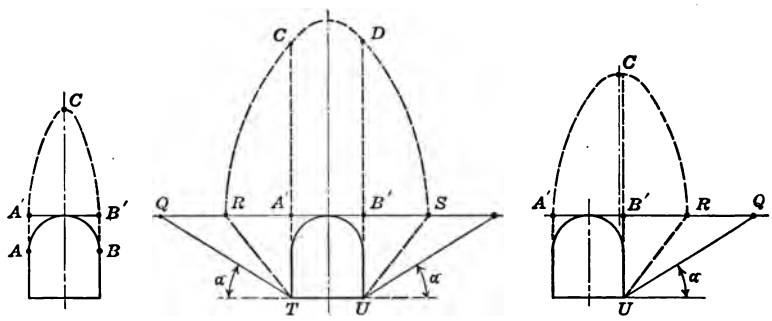


FIG. 99. FIG. 100. FIG. 101.

FIGS. 99–101.—Diagrams illustrating different cases of loading supported by the lining of deeply overlaid tunnels.

The load acting on the roof and floor of a tunnel driven through hard and solid material will therefore be limited by the line *A'-P-B'* and *C'-P'-D'*, Fig. 97. The location of *P* above the tunnel roof will depend on the width of the bore as well as on the cohesion of the overlaying material.

The load acting on the roof, floor and side walls of a tunnel driven through yielding materials will be limited by the line *t-P-t'-P'*, Fig. 98; the ground beyond these lines is supposed to have no action on the tunnel lining or timbering, provided unusual conditions such as geological faults, action of air or water on the rock, etc., will not cause unsymmetrical or excessive pressure. According to the geological formation and stratification of a site considered, the following cases of loading are encountered most usually in deeply overlaid tunnels: Case 1, Fig. 99. The pressure acts vertically, there is no sign of pressure on the side walls. The

lining should therefore be designed to carry the weight of the parabola *A-B-C*; for all practical purposes, the points *A* and *B* are assumed to be in *A'* and *B'*, located at crown arch elevation.

Case 2, Fig. 100. The pressure acts vertically on the arch; signs of weakness are noticeable in the side walls. The arch is to be designed to carry the weight *A'-C-D-B'*. If α represents the angle of repose of the material, it can be assumed for all practical purposes that the intersection of the line of rupture *T-R*, with a horizontal line passing through the crown of the tunnel arch, is located at a point half way between *Q-A'*, or at *R*. Therefore, the side wall *A'-T* is to resist the pressure due to the weight of the triangle *R-A'-T*, carrying the additional load *R-C-A'*.

Case 3, Fig. 101. The pressure is unsymmetrical to the center line of the tunnel; such a condition being caused either by the inclination of the strata, or the yielding of the materials on the right-hand side of the tunnel. In this case, the arch should be designed to resist the stresses caused by the weight of *A'-C-B'* and the side walls are to resist the pressure caused by the weight of *B'-R-U*, supporting the additional load *B'-C-R*.

Several formulæ that serve the purpose of determining the height of the parabola that represents the overlaying weight acting on tunnel linings have already been presented, but as it is beyond the scope of this book to present and discuss all of these, the Kommerell formula only, together with a table giving results for different kinds and conditions of materials are given here. The Kommerell formula is based on the deflection of the roof of a bore or tunnel, and as for the same kind of material, the deflection due to bending increases with the width of the bore, the height of the parabola becomes a function of the tunnel width and of the cohesion of the overlaying material.

Let *d*, Figs. 97 and 98, represent the deflection observed in a tunnel roof; let *C* have the value given in the following table,

VALUE OF COEFFICIENT "C"

Fine sand, dry	1.0
Sand, gravel	1.5
Earth, loam, etc.	2 to 4
Marl	4 to 5
Shale	6 to 7
Harder rocks	8 to 15

and *H* be the height of an ellipse substituted with sufficient ac-

curacy for all practical purposes to the parabola above the tunn roof; then

$$H = \frac{100.d}{C} \text{ the value of } d \text{ and } H \text{ being expressed in feet.}$$

The table following indicates that, in a tunnel driven throu sand, and with a roof deflection or settlement of 2 ft., H equal to about 133 ft. If the material penetrated is shale, will have an average value of 33 ft. In a deeply overlaid tunn C will have usually a value of 6 or more, for in such tunne rock only is usually encountered.

However, judgment is to be exercised in selecting the prop value for C, as a roof deflection of say 2 ft., may give H, value of 33 or 13 ft., according to whether the rock penetrat is soft sandstone or limestone, or harder rocks such as grani gneiss, etc.

VALUE OF C

D	1	1.5	2	4	5	6	7	8	10	12	1
	H	H	H	H	H	H	H	H	H	H	H
0.2	20	13	10	5	4	3.3	2.8	2.5	2	1.6	1.
0.4	40	23	20	10	8	6.7	5.7	5.0	4	3.3	2.
0.6	60	40	30	15	12	10.0	8.6	7.5	6	5.0	4.
0.8	80	53	40	20	16	13.0	11.0	10.0	8	7.0	5.
1.0	100	67	50	25	20	17.0	14.0	12.5	10	8.0	7.
1.2	120	80	60	30	24	20.0	17.0	15.0	12	10.0	8.
1.4	140	93	70	35	28	23.0	20.0	17.5	14	12.0	9.
1.6	160	107	80	40	32	27.0	23.0	20.0	16	13.0	11.
1.8	180	120	90	45	36	30.0	26.0	22.5	18	15.0	12.
2.0	200	133	100	50	40	33.0	28.0	25.0	20	17.0	13.
2.2	220	146	110	55	44	37.0	31.0	27.0	22	18.0	15.
2.4	240	160	120	60	48	40.0	34.0	30.0	24	20.0	16.
2.6	260	173	130	65	52	43.0	37.0	32.0	26	22.0	17.
2.8	280	186	140	70	56	47.0	40.0	35.0	28	23.0	19.
3.0	300	200	150	75	60	50.0	43.0	37.0	30	25.0	20.

In order to drive a tunnel economically, it is desirable to kn a priori the required thickness of the lining, which, in lo tunnels subjected to heavy rock pressure, may vary considerab The approximate load acting on the timbering of the headi can be determined also by observing the deflection of timb

subjected to bending stresses and also of those subjected to compression, and in this respect, the temporary timbering of the bottom heading, driven far in advance of the enlargement, will best show what can be expected when enlarging the bore to its full or normal section.

CHAPTER X

LINING DEEP TUNNELS

Having determined approximately the weight acting on a tunnel lining, the next step is to select the type of cross section best suitable to resist the stresses born by same. Theoretically, there is but one tunnel section that is most economical, corresponding to a given condition of loading; in actual practice, however, it would be unpracticable to change the tunnel section very often. Furthermore, certain clearance lines for the roll-

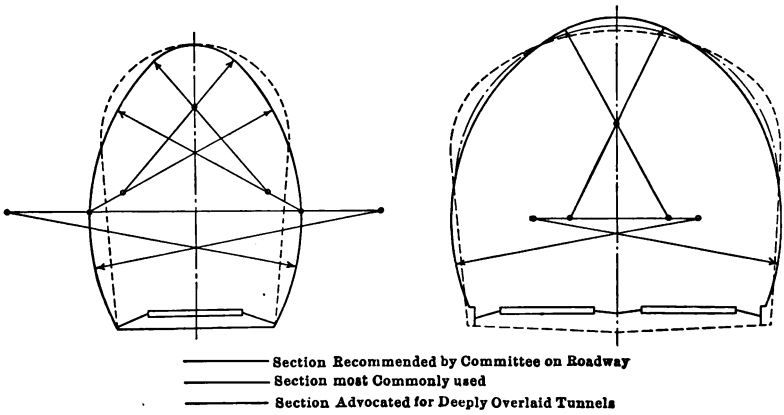


FIG. 102. FIG. 103.

FIGS. 102 and 103.—Cross sections for single and double track tunnels.

ing stock and for other purposes have to be strictly observed; it is also desirable that the masonry forms and tunnel centers be made as uniform as possible. For the above reasons it is usually the practice to design a few types of lining sections, the strength of which is determined a priori, adapting same where found necessary to conditions of loading. In deep tunnels, and in tunnels subjected to ground pressure, it is desirable to make the roof of the bore as narrow as possible thus making it self sustainable. In order to minimize the thickness of the arch, the thrust at the crown is reduced, by making the ratio of the arch span to the rise as small as conditions of clearance will permit.

The type of arch answering best the above requirements is that nearing the parabola; but, for reasons of construction, the arch is usually made up of segments of circles; straight lines are avoided altogether, and provision is made for future insertion of an invert, when deemed advisable.

Fig. 102 shows the section recommended by the Committee on Roadway, for single-track tunnels, together with that mostly used and advocated for deeply overlaid tunnels. The area of the last-named section is somewhat larger than the section recommended by the Committee. Fig. 103 shows the section recommended for double-track tunnels subjected to rock pressure,

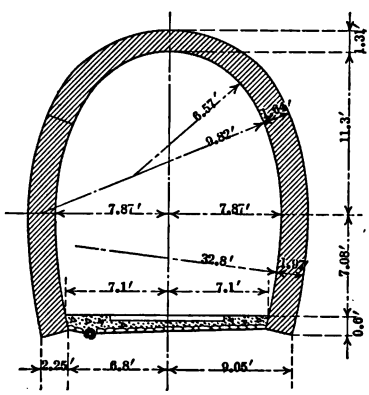


FIG. 104.—Standard section, Weissenstein tunnel.

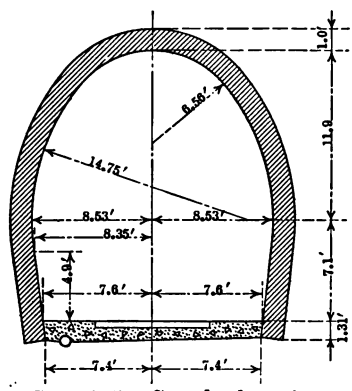


FIG. 105.—Standard section, Ricken tunnel.

together with the section used generally and that advocated for such tunnels. This last section has a somewhat less area than the section recommended by the Committee on Roadway, and a section equal to that used generally for double-track tunnels.

Figs. 104 to 111 show tunnel sections adopted for bores driven through various materials.

Materials Suitable for Lining Purposes

Opinions as to the kind and quality of materials best suitable to line deep tunnels, all aim toward the same results, *i.e.*, toward a material that will reach its maximum strength soon after being used, and that possesses a high compressive strength together with great resistance against action of water, heat,

frost and gases from locomotives. The question of strength is obvious, for the thicker the lining, the wider the bore, and the greater the amount of excavation and masonry.

On account of the small compressive strength of brickwork, the use in recent practice, in deep tunnel work, of brick lining has been closely limited. In general, local conditions decide whether rubble or concrete masonry, or artificial masonry blocks are to be used.

Rubble masonry, besides having a relatively low compressive strength, possesses the same disadvantages as concrete, *i.e.*, the

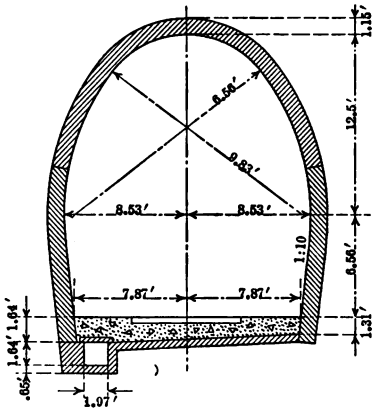


FIG. 106.—Standard section, Granges tunnel.

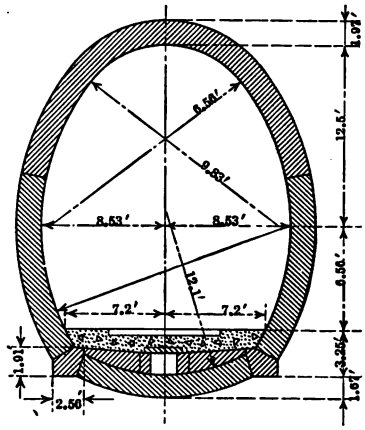


FIG. 107.—Heavy section, Granges tunnel.

maximum strength is reached only after being laid, and, in wet sections, or in heavy pressure zones, both of these materials have proved to be rather unsatisfactory. In dry sections and where the lining answers merely the purpose of preventing falls of rock, concrete may often be found cheaper than stone masonry, although one must bear in mind that, for construction reasons, it is necessary to give concrete tunnel arches a minimum thickness of 22 to 24 in. whereas dressed stone masonry or concrete blocks can have a thickness of only 14 in.

Concrete and artificial masonry blocks are being much favored, and in general, have given much satisfaction both during and after construction. Such blocks possess the advantage of being manufactured in advance, and when used they have already reached a high compressive strength. They can be placed more rapidly than dressed stone or brick masonry,

and as the compressive strength of artificial or concrete blocks is more uniform than stone- or brickwork, a smaller factor of safety can be used. Plain concrete blocks have been used in connection with the lining of several tunnels; for instance, blocks

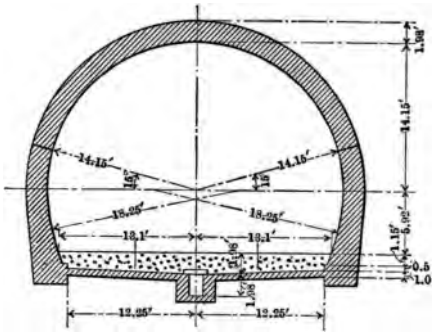


FIG. 108.—Standard cross section, Mont d'Or tunnel.

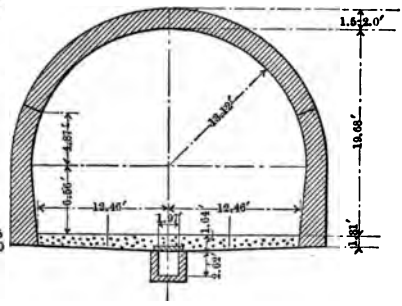


FIG. 109.—Standard cross section, Loetschberg tunnel.

having an ultimate strength of 1200 to 2000 lb. per sq. in. were used extensively in lining the first bore of the Simplon tunnel. Similar blocks possessing an ultimate strength of 2500 lb. per sq. in. were used in lining the double-track Loetschberg tunnel.

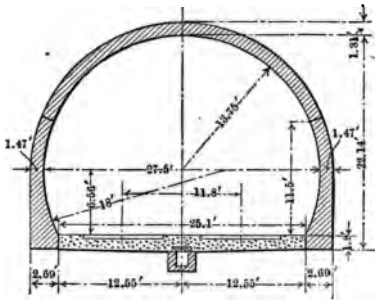


FIG. 110.—Standard cross section, Hauenstein tunnel.

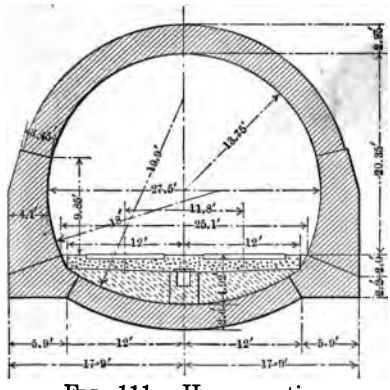


FIG. 111.—Heavy section, Hauenstein tunnel.

The lining of the Hauenstein double-track tunnel and part of the second bore of the Simplon tunnel consist of artificial masonry blocks having, when placed, 70 per cent. of a guaranteed ultimate compressive strength of 2844 lb. per sq. in. These blocks, when

tested, were found to have an ultimate strength of 4000 to 5000 lb. per sq. in.

Concrete blocks have been used also extensively in lining the single-track Granges tunnel, and interlocking concrete blocks of the type illustrated by Fig. 112 have found their adaptation in lining the Mount Royal tunnel.

The following table gives the size of concrete blocks used in connection with the lining of long tunnels:

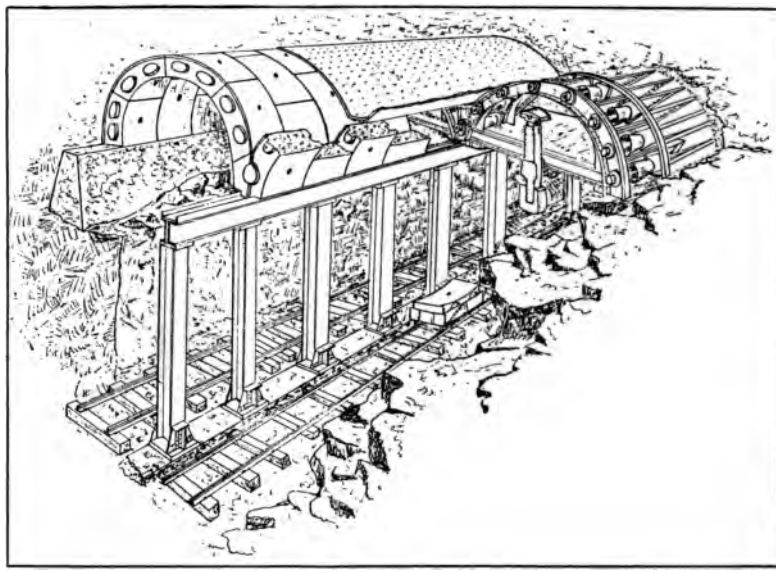


FIG. 112.—O'Rourke interlocking concrete blocks as used in connection with the lining of the Mount Royal tunnel.

Name of Tunnel	Size of Blocks
Granges tunnel	9.5 × 4.6 × 23.0 in.
Arthur pass	12.0 × 9.0 × 18.0 in.
Weisenstein	14.0 × 6.3 × 14.0 in.
Mexican Central Ry	8.0 × 9.0 × 20.0 in.
Rosenberg	7.9 × 13.8 × 19.7 in.

Probably the most striking contrast in the methods used to line short, as compared with long tunnels, lies in the procedure followed during construction. While short tunnels have and are still being lined with timber, and often are completed without lining at all, the practice followed by builders of long and deep tunnels, is to line their tunnels with masonry throughout, in most instances, making the lining closely follow the excavation.

In order to prevent further movement of the overlaying strata, and also to distribute the load evenly over the masonry lining, no voids are left outside of same, concrete or spalls only being used to fill voids caused by excess excavation or cave-in, and no timbering is left within the lining.

It is obvious that tunnels built under such conditions are bound to give satisfaction and can be proportioned so as to minimize the amount of masonry and excavation, thereby reducing transportation charges during construction.

Determination of Stresses in the Lining

Having determined the weights acting upon the lining and having selected the shape or cross section of the tunnel and of its lining, also the materials suitable for lining purposes, the stresses at the arch crown, haunches, and footings are then ascertained according to methods best suitable for this purpose, bearing in mind that hair splitting would be waste of time, as the weight acting on the lining can be determined but roughly at best. A large factor of safety should be used in proportioning the various sections of the lining for the following reasons:

1. It is often necessary to place or erect certain sections of the lining hurriedly, to take care of swelling of the ground or crushing of the timbering, sometimes in presence of water or springs, spouting under high pressure, and the work thus accomplished is unavoidably of inferior quality.

2. The stresses caused by the weight acting upon a bore may be different in the course of years from those assumed or supposed to exist during construction, the difference being due to various causes such as unequal movements or settlement of the surrounding strata.

3. In certain formation, and especially in limestone and other aqueous rocks, underground streams may find an outlet in the tunnel, and through decomposition of the material penetrated, water may accumulate back of the lining and exert hydrostatic pressure of such intensity as to cause partial or even total failure of the lining.

When upward pressure is experienced, the determination of stresses in the arch, side walls and invert is somewhat more complicated. The forces counteracting those due to upward pressure on the invert, are the materials overlaying the bore

the weight of the lining, and the friction between the tunnel lining and the adjacent rock.

Fig. 113 illustrates the distribution of pressure acting on a tunnel, as presented by E. Wiesmann, an engineer who has devoted much time to the problem of ground pressure on tunnel lining, and more especially in connection with the Hauenstein tunnel. The upward, or active pressure acting on the tunnel invert, exerts a horizontal thrust or reaction, at the foot of the side walls, which is resisted passively by the surrounding rock.

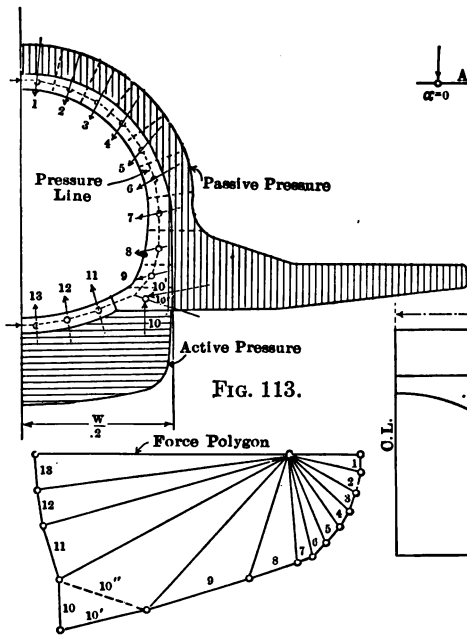


FIG. 113.

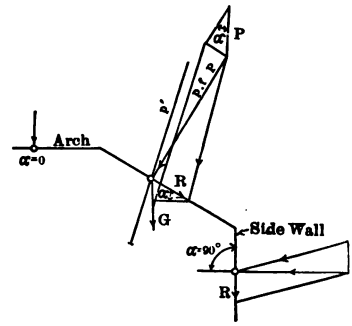


FIG. 115.

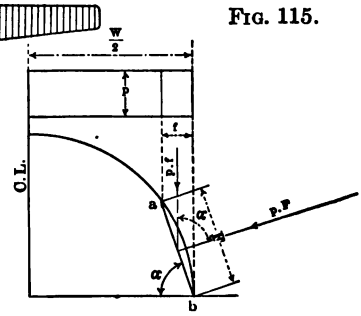


FIG. 114.

FIGS. 113 to 115.—Diagrams illustrating distribution of ground pressure on a tunnel lining.

This pressure decreases above the side walls, and becomes normal to the tunnel arch.

In certain sections of the Hauenstein tunnel, the vertical or active pressure, acting on the tunnel invert was taken as 24 tons per square meter (4910 lb. per sq. ft.).

In Fig. 114 let p represent the pressure, then, over a distance

$a\text{-}b = F$ of the arch, the pressure is equal to $p.f = p.F. \cos \alpha$. The pressure perpendicular to $a\text{-}b = \dfrac{p.f}{\cos \alpha}$

The friction $R = u.p. \sin \alpha$ (see Fig. 115) where u = friction coefficient taken as 0.30 in the example referred to above.

The resultant P' is determined with the assistance of p, R and G, G being the weight of the masonry.

$\alpha = 0$ and $90°$ at the arch crown and side walls respectively.

Drainage of Tunnel Linings

In modern tunnel work, two methods are used most exclusively to drain water that accumulates back of the masonry or concrete lining. One method consists in preventing water to

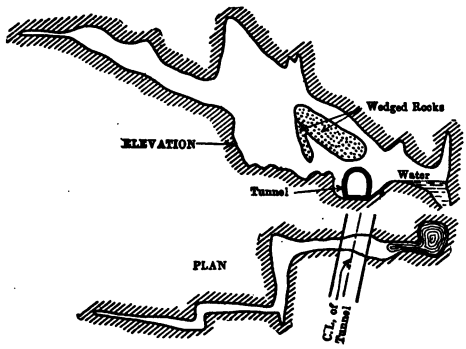


FIG. 116.—Cave in limestone formation, 1615 meters from south portal, Granges tunnel.

find a path to the tunnel, thereby causing water to accumulate back of the lining, hence in the strata, and then to find another outlet.

The other method consists in providing adequate drains or conduits in the lining, thereby assisting underground springs in following lines of least resistance. Both methods have their disadvantages, but the first method seems to be most adequate, for it prevents water to exert its eroding effects on the strata surrounding the bore.

In rocks of aqueous formation, springs finding an outlet in the tunnel through the lining, aim to enlarge their original channel or path by mechanical or chemical action, thereby causing voids to be created in the strata.

Fig. 116 illustrates a case encountered and liable to be en-

countered often in driving a bore through limestone formation. Fortunately, in this example, the cave formed by the mechanical action of water, was struck during construction of the tunnel, and adequate precautions were taken to drain it, thereby preventing water from exerting pressure on the side walls or arch of the tunnel.

The chemical action of water underground, is illustrated in one case by Fig. 117 being a cross section of the Simplon tunnel on the south side of the range, as prepared by Prof. Schardt who made an exhaustive study of the hydrology during the construction of this bore.

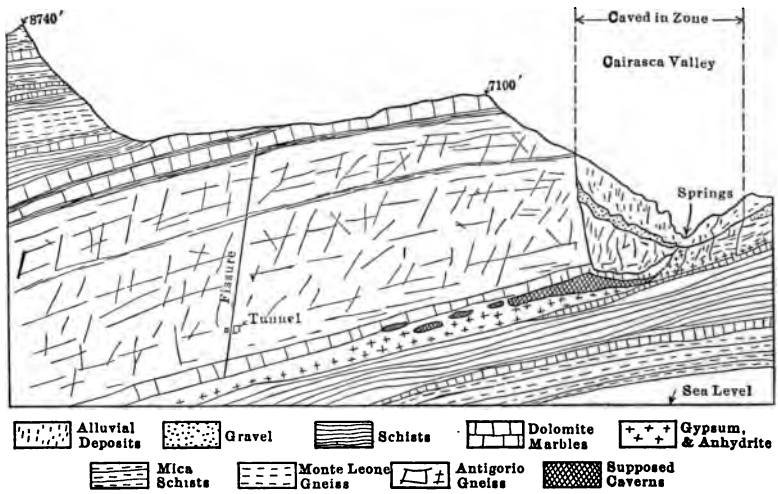


FIG. 117.—Cross section of Simplon tunnel Massif, 3860 meters from south portal.

It had been noticed that sections of land in the Caircasa Valley were caving-in, and no satisfactory explanations had been found, accounting for this phenomenon, until Prof. Schardt, through an analysis of certain springs spouting in the Simplon tunnel, found that some 5000 cu. yd. of material are being carried away, yearly, through the chemical action of water, thereby causing caves to be formed under and in the vicinity of the Caircasa Valley.

In materials subjected to erosion, it is preferable to make the masonry lining impervious to water, leaving no voids between the lining and the rock. This can be accomplished by filling

the space between the lining and the rock with concrete, or by filling it with spalls and then grouting the voids left under pressure. This last method, although expensive, possesses the advantage to fill also seams in the rock, thereby strengthening the surrounding strata.

In materials less subjected to erosion and when the amount of water encountered is small, dry packing is used, and drains leading to the tunnel drainage canal or conduit are then provided in the masonry.

Waterproofing the lining has been used also in certain instances to prevent water from oozing through the arch lining. Probably the most satisfactory type of waterproofing is obtained

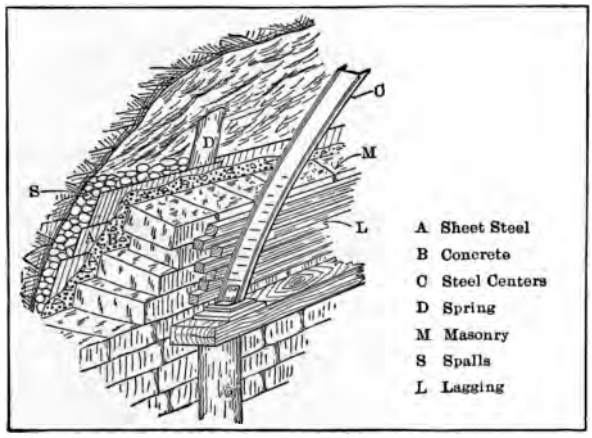


FIG. 118.—Sketch showing method of building the masonry lining of the Simplon tunnel.

by providing the extrados of the arch with a coat of 1 to 2 in. of rich cement mortar, this material being less subjected to the chemical action of water, or to be punctured by spalls or protruding rocks, as would be for instance, the several kinds of felts or waterproofing membranes found on the market.

TUNNEL DRAINAGE CANAL

The topography of a tunnel site and considerations of traffic usually determine the grade of a tunnel and incidentally also of its drainage canal or conduit.

Usually but little data are available to determine the cross section or carrying capacity of tunnel drainage canals owing

to the uncertainty as to the amount of water to be taken care of, and as it is necessary to carry the canal close to the heading's face so as to insure adequate drainage during construction, judgment and skill are required in selecting the type and in giving the proper dimension to the canal of long tunnels. Gases encountered and poor ventilation excepted, there is nothing more discouraging or that will lower the efficiency of tunnel crews than to work knee deep in water.

In relatively dry tunnels, circular tile or cement drains have been used, as for instance in the Ricken tunnel; in the completed bore of the Simplon tunnel, the drainage canal consisted of a semicircular concrete conduit, water being conveyed at intervals to the main canal in the auxiliary bore through the cross galleries.

In wet tunnels, the canal is usually blasted out of the rock and then lined with concrete or stone masonry; for reasons of construction it is given generally a square or rectangular cross section. Sometimes, a combination of circular drains are used in the upper part of the bore, that is, toward the summit of the grade where the amount of water to be taken care of is relatively small, and a rectangular canal is used toward the portal; this method of procedure was followed in the Weissenstein tunnel.

The following table gives the dimensions of tunnel canals as actually built:

Name of tunnel	Number of tracks	Width of canal, in.	Depth of canal, in.	Area of canal, sq. ft.	Location of canal
Simplon.....	1	23.6	19.7	3.2	Side
Loetschberg.....	2	23.6	23.6	3.87	Center
Granges.....	1	23.6	39.5	6.5	Center
Weissenstein.....	1	19.7	19.7	2.57	Side
Arthur Pass.....	1	18.0	18.0	2.25	Side
Ricken.....	1	12.8 D	.....	0.78	Side
Hauenstein.....	2	15.7	19.7	2.15	Center

In single-track tunnels, the canal or conduit is located at or near the footing of a side wall, as shown in Fig. 106. When a masonry invert is required, the canal is located either near a side wall or in the center of the bore, under the track (Fig. 107). This last method has the disadvantage to make the access to the

canal rather difficult unless manholes are provided, but it enables the masonry invert to be built symmetrically about the center line of the tunnel.

In double-track tunnels, the canal is located at or near the center of the bore, between the tracks, as shown in Fig. 108. Removable reinforced concrete slabs have been used extensively to cover the drainage canal of tunnels, to prevent débris and track ballast from obstructing it; they also make possible the inspection, cleaning and eventually repairing of the canal.

Having determined or assumed the amount of water to be taken care of, the area of the canal can be determined readily by the following formulæ or method:

The area A of the canal is equal to $\frac{Q}{V}$

$$\text{Where } V = c\sqrt{r.s} \text{ and } c = \frac{87}{0.552 - \frac{m}{\sqrt{r}}}$$

$$D = A.V$$

in the above D is the discharge of the canal in sec. ft.

r is the hydraulic radius, being equal to $\frac{p}{A}$ where p is the wet perimeter of the canal (in feet).

s = slope of canal.

A = area of canal in square feet.

M = a constant which has the following values:

for smooth C.I. and cement pipes or concrete canals with very smooth finish $m = 0.21$

for somewhat rougher C.I. and cement pipes and concrete with smooth finish $m = 0.36$

for concrete canals with rough walls $m = 0.50$

The value of m depends on the type and care with which the canal has been constructed. For practical purposes m should be made preferably 0.36 or 0.50.

The wet perimeter of the canal or conduit should be made as smooth as practicable, thereby reducing frictional resistances and increasing their carrying capacity.

CHAPTER XI

DETERMINATION OF THE ROCK TEMPERATURE IN DEEPLY OVERLAID TUNNELS

GENERAL

The capital involved in the first cost of tunnel ventilating and refrigerating plants, together with that of their operation and maintenance, is far from being a small fraction of the total cost of a bore, and this has led for the past 25 years, to interesting studies, serving the purpose to determine at the outset the rock temperature to be encountered when driving deep tunnels. It is only within the past 10 years that the combined efforts of noted geologists and engineers as for instance Stapf, Königsberger, Heim, Smidt, Schardt and others, have resulted in developing sound theories based on experiments and careful observations. Discouraging and incorrect results led to criticisms from persons either ignorant or sceptical as to the practical value of the problems involved, directed against men who, often, without any pecuniary benefit had spent many days several thousand feet underground at temperatures over 120° F. or else on top of high peaks at temperatures far below zero. On too many occasions, it has been forgotten that one must not demand from men more than man can do.

Information Required

On account of the broad field covered involving the latitude, longitude and altitude of a particular tunnel location, it is not possible to publish information or data suitable to any and all conditions.

Briefly enumerated, the following data are required to determine exactly the ground temperature under peaks, mountain ranges or in similar places:

1. The latitude, longitude and altitude of the site considered.
2. The climate and hydrological conditions.
3. A geological cross section of the mountainous range or peak to be penetrated by the proposed tunnel, showing the kind of

materials expected to be encountered, the stratification of said materials and the dip of the strata.

4. An accurate longitudinal section on the axis of the proposed tunnel and cross sections at a few stations along the tunnel axis, for a distance on each side of said axis equal to the overlaying depth above the tunnel.

5. A detailed geographical map showing streams, forests, and like features if any.

6. The temperature of the ground surface, along and above the tunnel axis, or:

7. The yearly average air temperature at different elevations, at or near the tunnel site.

Items 1, 2, 4 and 5 are usually obtainable at a nominal expense of time or money, but items 3, 6, and 7 are not always readily obtainable if at all.

In Central Europe, where a number of long and deep tunnels have been driven, beginning in the year 1857 with the Mont Cenis tunnel, numerous observations as to aerology, ground temperature and geology have been carried on year by year, so that much accurate data are available. In this country, the U. S. Geological Survey as well as the U. S. Weather Bureau have for years, accumulated a large amount of valuable data practically throughout the country. However, little data are available relating to the ground temperature, although temperatures of the ground have been recorded in several mines, shafts and wells sunk in relatively flat countries and valleys.

These observations are of little value for our purpose, there being a great divergence between the value of the geothermic gradient under flat countries and mountains.

Value of the Geothermic Gradient

In 1857 already, observations were made by Walferdin, in Luxemburg, in artesian wells and bore holes for the purpose to determine the value of the geothermic gradient. In one of these, 2400 ft. deep, the increase in temperature was found to be 1° F. for 56 ft. Thereafter, numerous observations serving the same purpose were made in England, Germany, France and Austria.

Three hundred eighty-four temperature measurements were made by Kobrick in a bore hole 6600 ft. deep, in upper Silesia. The maximum ground temperature at the bottom of

the hole was found to be 165.7° F. The geothermic gradient was about 64 ft. per deg. F.

In the following table are given values of the geothermic gradient as observed by James Sterling in the Bendigo mines in Australia:

Depth in feet	Gradient, in feet per deg. F.
425	100
1294	182
1750	173
2295	152
2700	137
3110	110
3250	111
Average gradient	138 ft.

The following table gives values of the geothermic gradient recorded in wells, mines, shafts, etc., in relatively flat countries:

Location	Gradient, in feet per deg. F.
Schladebach	64.0
Pittsburg	62.0
Spirenburg	58.0
Paris artesian wells	56.0
London artesian wells	55.0
Yakoust, Siberia	52.0
St. Petersburg wells	44.0
Slit mines, Weardale	34.0
Ruhr coal fields	51.0
Saarbrucken mines	50.0
Mondorf, Luxemburg	56.5
Newcastle coal fields	42.5
Sudenburg	59.0
Kertish Town	65.0
Average gradient	53.5

W. S. Henwood states that in Cornwall, copper bearing lodes are hottest and gives the following values of the gradient: Tin lodes 40 ft. Tin and copper lodes 39 ft. Copper lodes 38 ft. per deg. F.

Abnormal geothermic gradients, *i.e.*, gradients affected by unusual conditions such as carboniferous or metalliferous or volcanic deposits, etc., have also been observed in various countries. Geothermic gradients varying from 20 to 30 ft. only per

deg. F. have been recorded, and in a bore hole of the Calumet and Hecla Mining Co. in the peninsula of Kewesnaw, the geothermic gradient was found to be 224 ft. per deg. F.

E. Thoma states that a most abnormal case was recorded in the mercury mines of Idria; at a depth of about 490 ft. below the ground surface, the gradient was 13 ft. per deg. F. in a horizontal direction and 5 ft. vertically.

Value of the Geothermic Gradient under Mountains, Peaks, etc.

Experiments carried on during the driving of the Mont Cenis tunnel had demonstrated that under mountains, the increase in temperature of the ground was less than under valleys or flat land. As a matter of fact, it had been observed that all things being equal, the geothermic gradient was least under valleys which offer less radiating surfaces than flat countries and mountains.

The following table gives the value of the gradient recorded in various tunnels:

Name of tunnel	Gradient, in feet per deg. F.
Tauern	70
Loetschberg	87
St. Gothard	86
Mont Cenis	79
Simplon	65
Albula	64
Arlberg	64
Ricken	62
Hauenstein	64
Average	64 ft.

This table indicates that under mountains, the geothermic gradient is about 33 per cent. greater than that under valleys or flat countries.

Further observations had led to the belief that the cause of the variation in the geothermic gradient was due to the following reasons: 1. The profile or shape of the ground, as for instance mountains, peaks, valleys, or the existence of large bodies of water, such as rivers, lakes, etc. 2. The existence of radioactive substances able to give out heat by oxidation or otherwise. 3. The existence of volcanic substances such as

magmas. 4. The difference in the conductivity for heat of different materials. 5. The difference in the conductivity for heat of rocks in the line of or across the stratification. 6. The presence in the ground of flowing water.

Since no tunnels have yet been driven at any great depth under large bodies of water, it has not been possible to ascertain the influence of the same on the geothermic gradient, and as most experiments and observations have been carried on while driving Alpine tunnels, it has been found impossible to ascertain the effect of volcanic matters on the gradient. On the other hand, the radioactivity of radium has been found to have no appreciable influence on the gradient, even in the mines of the Joachim Valley where a large quantity of radium has been extracted.

Much has been said about the heat conductivity of rocks. The valuable experiments carried on by Prof. Golz indicate that dry rocks have nearly uniform heat conductivity as shown by the following table:

Kind of rock	Conductivity[1]
Antigorio gneiss (with biotite)	2.60
Antigorio gneiss (with feldspar)	2.12
Antigorio gneiss (with granite)	1.95
Aare limestone (with aplitite)	1.55
Para gneiss	1.80
Valdagranda gneiss (with hornblende)	1.65
Rofna porphyry (with felsite)	2.10
Phyllite (metamorphic)	2.60
Troas limestone (Titton)	1.85
Pontis limestone (with phyllite)	1.80
Limestone (with phyllite)	1.80
Andesite	1.18
Quartz	2.40
Hornblende schist	1.20
Mica schist	1.80
Quartz mica schist	1.50

From this table it will be readily noticed that the thermal conductivity of various rocks cannot have a marked influence on the gradient, and that other reasons must be sought for the wide divergence of the gradient.

[1] The conductivity is expressed in kilogram-calories per meter per hour, the thermal conductivity of glass having an absolute conductivity of 2.6, being taken as unity.

Experiments on heat conductivity of specimen of dry and wet rocks gave the results shown in the following table:

THERMAL CONDUCTIVITY OF VARIOUS ROCKS WHEN DRY AND WET

Kind of rock	Conductivity Dry rocks	Conductivity Wet rocks
Antigorio gneiss	1.44	1.39
Maigel gneiss	1.36	1.34
Sella gneiss	1.30	1.20
Phyllite	1.11	1.01
Limestone phyllite	1.13	1.10
Schist (granitic)	2.79	2.32
Schist	1.93	1.78

This table shows that ordinary wet rocks have a better conductivity than dry rocks and that the gradient for wet rocks is from 4 to 10 per cent. smaller than for dry rocks. As a general rule, it can be said that the thermal conductivity of rocks is a factor of secondary importance with respect to the value of the geothermic gradient.

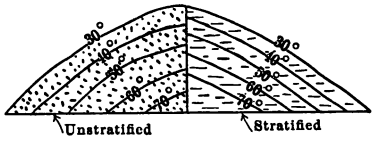


FIG. 119.—The geothermic gradient for unstratified rock is greater than for stratified rock since the former has a better conductivity.

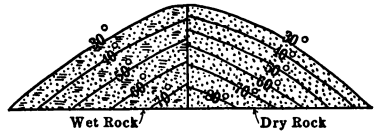


FIG. 120.—The geothermic gradient is greater for wet rock than for dry rock since the former has a better conductivity.

Further observations and experiments led to the discovery that the thermal conductivity across and in the line of stratification or cleavage was not the same. The observations made on specimens of rocks taken in the Simplon tunnel, as given in the table below, illustrate the amount of this divergence.

THERMAL CONDUCTIVITY OF VARIOUS ROCKS, ALONG AND ACROSS STRATIFICATION OR CLEAVAGE

Granite along the strata	2.49
Granite across the strata	1.94
Schist and gneiss along the cleavage	3.02
Schist and gneiss across the cleavage	2.28
Calcareous schist and limestone along the cleavage	3.26
Calcareous schist and limestone across the cleavage	2.10

Since rocks in masses possess less broken surfaces than rocks in layers, the thermal conductivity for the latter is not as high

as the former. Figs. 119 to 122 will best illustrate the effect on the geothermic gradient due to the causes described above. It is assumed that the temperature at the surface of the ground is uniform at any point or elevation, a condition which does not occur in practice; also that the mountain or peak is symmetrical about a vertical center line, except as noted.

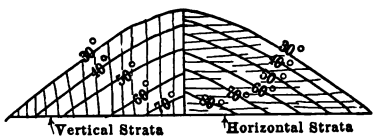


FIG. 121.

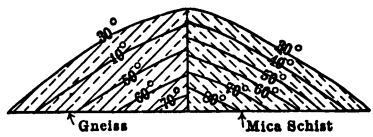


FIG. 122.

FIG. 121.—The gradient is greater for vertical than for horizontal strata since the thermal conductivity is greater along the stratification or cleavage.

FIG. 122.—Since mica schist is a very poor heat transmitter the gradient for it is much smaller than for gneiss or granitoid rocks.

The table below gives values of the geothermic gradient entirely reliable when the kind of rock penetrated, the degree of dampness of same and the inclination of the strata are known. These values hold good only for determining the rock temperature under mountain peaks and in similar places, when the effect of volcanic matters, or ores, carboniferous deposits or substances to give out heat by oxidation is not anticipated.

Materials	Dry materials, ft.	Wet mat., ft.	Vertical stratific, ft.	Horis. strat., ft.	Inclined less than dry, ft.	Strata. 45° w. hor. wet., ft.
Granite, Limestone, Shale, Clay	60–62	65–67				
Sandstone	51					
Gneiss, Schist, Protogine	.....	.....	64–67			
Dry gneiss	.....	.....	.....	51–53		
Phyllite	.....	.....	.....	55–57		
Mica schist	44–49	47–53				
Gneiss	.....	.....	.....	.....	54	57
Phyllite	.....	.....	.....	.....	58	61
Mica schist	.....	.....	.....	.....	52	54

Variation of Geothermic Gradient with Depth

It has also been observed that the increase of the ground temperature at a certain depth ceased to be a direct function of the overlaying depth; although, other things being equal, the gradient decreases as the depth increases and thus becomes a function of the overlaying and surrounding masses. Assuming, for instance, that for the first 100 ft. below the ground surface, the geothermic gradient is 60° F. at a depth of 5000 or 6000 ft., the gradient might be only 55 or 56 ft. This phenomenon complicates the problem, although the error involved is small for overlaying depths of 3000 to 5000 ft.

Prof. Konigsberger and E. Thoma have developed a theory enabling the geothermic gradient to be computed by taking into consideration the form of the overlaying masses. Besides being somewhat complicated for practical use, and on account of the wide divergence in assumptions that may be made for the proper value of several elements embodied in the formulæ, it is a question whether the results obtained by the application of such a theory warrants its adaptation to practical purposes.

It must be admitted, however, that the results obtained by the application of the theory referred to above has given entire satisfaction on several occasions.

Influence of Water on Geothermic Gradient

A factor of far greater importance than any yet named for its effect on the gradient is the occurrence of water or springs while driving a tunnel.

The large quantity of water met in the Bosruck tunnel had caused the observed rock temperature to be 41 per cent. less than that expected. A similar phenomenon was observed while driving the Simplon tunnel, thus again causing a wide divergence between the prognosticated and the observed temperatures.

While driving this tunnel, it was observed that water flowing downward or spouting from the roof of the tunnel had a cooling effect on the surrounding rock, while water spouting upward or from the invert or floor of the tunnel was warm, its effect being to increase the rock temperature. This phenomenon is explained by the fact that hot water came from great depths, and therefore had acquired very nearly the high temperature existing at such

depths, while cold water flowing downward came directly from the surface of the ground, sometimes at a high elevation, and had travelled through but a relatively short depth of overlaying materials.

Water spouting in small quantity all along a tunnel has a more cooling effect on the rock temperature than large quantities of water spouting at one or few points.

All things being equal, a decrease in the rock temperature always indicates a nearby inrush of water. It has been found that water is usually to be expected in tunnels driven through limestone, while granite or schist or gneiss, stratified horizontally are more favorable in this respect. It is, therefore, very important when prognosticating the rock temperature to be encountered, to make a thorough study of the rainfall, the discharge of nearby streams and the dampness of the ground in order that the possibility of the occurrence of water in the strata penetrated may be to a certain extent determined.

Influence of Water on Rock Temperature in the Weissenstein, Granges and Simplon Tunnels

The Weissenstein and Granges tunnels are typical examples of bores, the rock temperature of which has been affected practically throughout their length by underground springs, while that of the Simplon tunnel was affected chiefly by large bodies of water.

Fig. 123 is a geological profile of the 12,150 ft. long Weissenstein tunnel, driven almost entirely from the south portal only, where a maximum water discharge of 16 sec. ft. was recorded. Small springs were encountered throughout the tunnel length, thus resulting in lowering the rock temperature and increasing the value of the geothermic gradient. Normally, the gradient should have been 67 ft. for wet limestone, yet, at elevation 8347 ft., for instance, the ground temperature at the surface is about 43° F.; the overlaying depth at this point is 1537 ft., and the rock temperature recorded in the bore was 49.6° F. only. This makes the gradient 233 ft. per deg. F. It must be noted here, however, that the material penetrated by this tunnel cannot be classified as wet limestone, but rather as limestone thoroughly saturated with water. The seepage in the tunnel varied according to the season, being a maximum in April during the rainy season, as indicated by Fig. 124.

The North slope of the mountain marked "*A*" on Fig. 123 is well covered with thick woods, acting as a storage reservoir and contributing greatly to cool the rock below, especially at the point where the strata are practically vertical. The vertical stratification at "*D*" resulted also greatly in keeping down the rock temperature in the tunnel. The temperature variation between the points "*A*" and "*B*," having nearly the same elevation is due chiefly to the different stratification and exposure of the ground surface to the sun's rays.

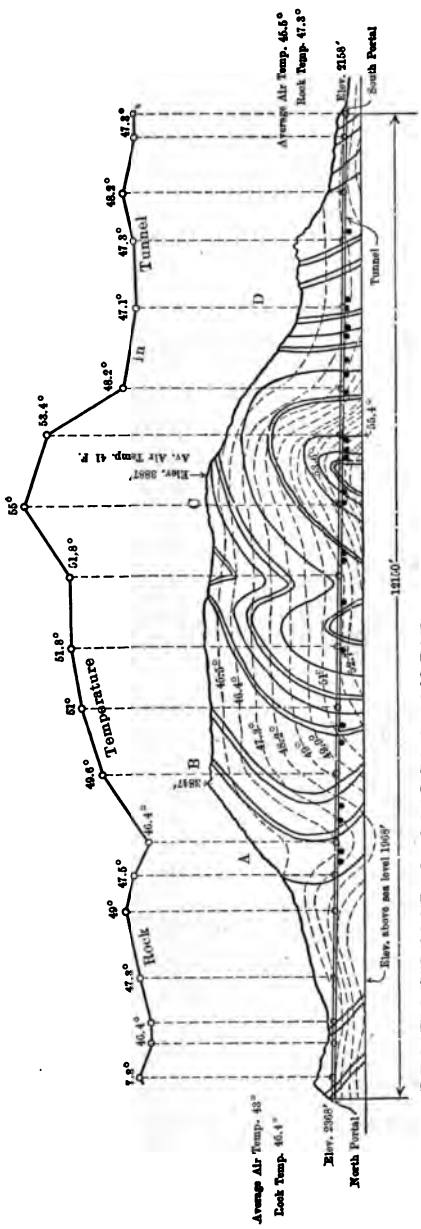


FIG. 123.—Geological section of the Weissenstein tunnel showing the distribution of ground temperature.

Conditions very similar to those referred to above were met in driving the 28,093 ft. long Granges tunnel, as illustrated by Fig. 125. In this case, however, the material overlaying the bore was somewhat less saturated with water, and the geothermic gradient was nearer to the value found under normal conditions. For instance under elevation 4494 ft. where the ground temperature is about 41° F. the overlaying depth is 2790 ft. and the rock temperature recorded in

the tunnel is 67° F., thus making the gradient 103.5 ft. per deg. F. Under the summit the elevation of which is 4067 ft. the gradient was found to be 129 ft. per deg. F.

In well-stratified formation, the maximum rock temperature will be found usually under an anticline, for in such a case the roof-like or vaulted shape of the strata forms a natural barrier to water. This phenomenon is quite noticeable in the case of the Weissenstein and Granges tunnels.

From observations made by Prof. Konigsberger, it results that each 12 sec. ft. of water spouting from a point in a tunnel

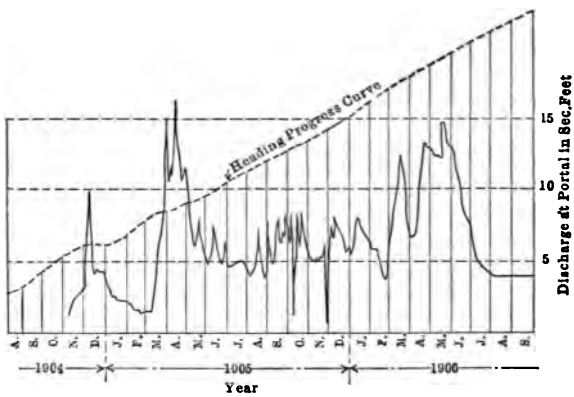


FIG. 124.—Driving progress curve in heading and discharge of underground water as measured at south portal of Weissenstein tunnel.

decrease the geothermic gradient by 15 per cent. for a surrounding distance from the spouting point of 6000 to 7000 ft.

Accumulation of Heat

The Ricken tunnel (see Fig. 93), driven through sandstone and conglomerate formation, offers a striking difference to the tunnels referred to above. Practically no water was encountered here, and this feature resulted in decreasing the geothermic gradient down to 51 ft. per deg. F. The average rock temperature was found to be about 66° F. On account of the existence of coal, methane (CH_4) was encountered, which, by becoming ignited, increased the rock temperature to 152° F. regardless of the cooling effect of the then existing powerful ventilation.

Soon after the fire had been smothered, the rock temperature fell down to 66° F. again; this shows that underground a small

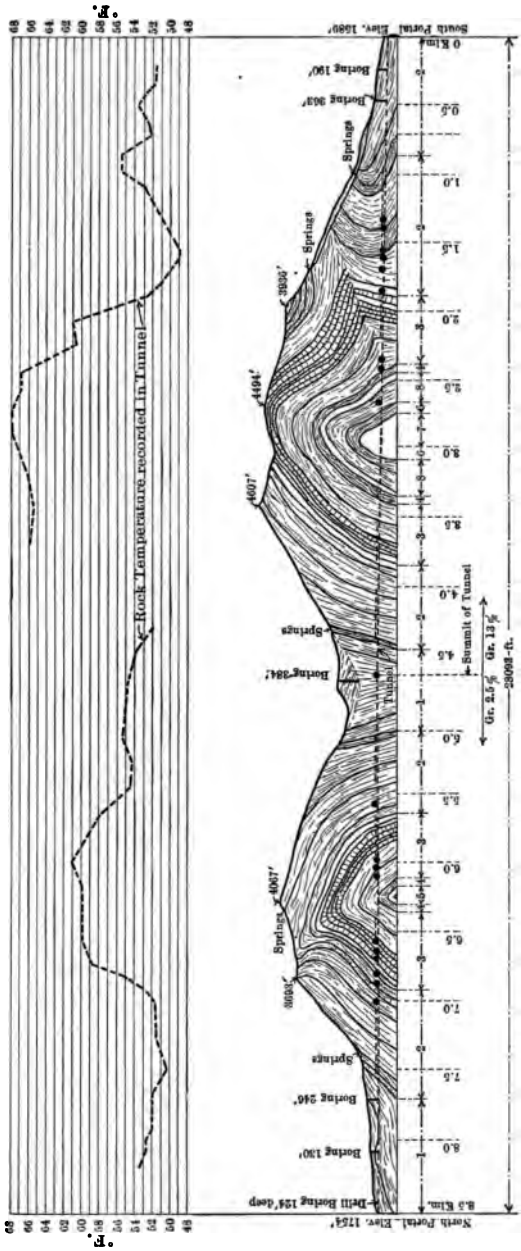


FIG. 125.—Longitudinal geological section, Granges tunnel.

amount of heat will greatly increase the rock temperature; on the other hand, a small amount of heat removed will materially decrease it.

This phenomenon was best observed when driving the Simplon tunnel; in order to obtain reliable information, the ventilation was stopped in one of the headings, in which a rock temperature of 127° F. was recorded after 12 hr., in a hole 10 ft. deep, as compared with 123° F. with the ventilation. With continued ventilation, the rock temperature decreased by 10° in a few days, and by 18 and 36° F. after 14 and 90 days respectively.

Temperature of the Ground at the Earth's Surface

In order to be able to determine accurately the rock temperature to be encountered in tunnels, it is of the utmost im-

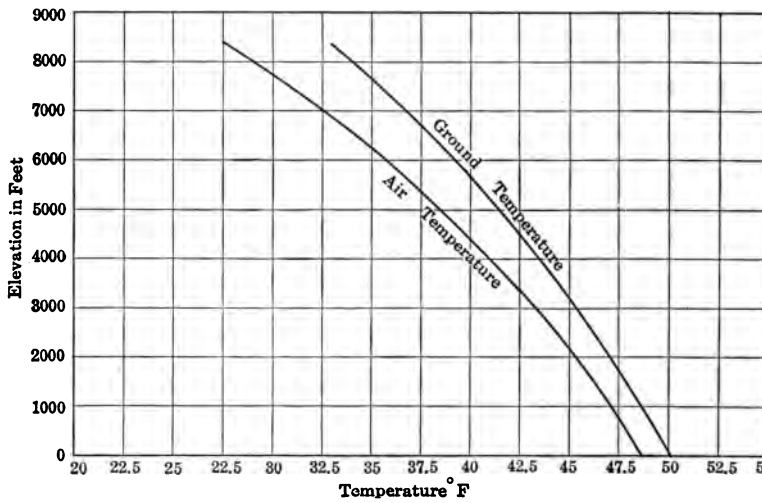


FIG. 126.—Air and ground temperature curves as recorded in central Europe.

portance to know first the temperature at the surface of the ground above the tunnel. It is a well-known fact that for the same latitude and longitude, the air temperature is not the same, and that the ground temperature is not the same for different exposures to the sun's rays, dampness or dryness of the ground and assimilation of the air temperature. The following table gives results of observations made in central Europe, in bore holes 7 to 30 ft. deep, from which a diagram has been plotted (see Fig. 126).

Elevation, ft.	Ground temp.	Air temp.	Diff.	Elev., ft.	Ground temp.	Air temp.	Diff.
490	50.5	48.5	2.0	4270	43.0	.....	.....
985	49.5	47.4	1.9	4400	43.7	40.4	3.3
1055	48.5	.....	.....	4420	42.4	.....	.....
1150	48.5	47.0	1.5	4650	40.7	37.9	2.8
1170	46.7	47.0	0.3	4920	42.0	.....	.....
2170	47.3	45.5	1.8	4950	41.3	37.6	3.7
2370	46.4	43.1	3.2	5800	40.0	35.1	4.9
2970	44.8	42.4	2.4	6070	38.0	.....	.....
3000	47.0	.....	.....	6560	37.7	36.5	1.2
3280	46.0	.....	.....	6630	36.3	.....	.....
3370	46.0	48.5	2.5	6900	36.5	.....	.....
3440	43.7	42.0	1.7	6920	37.2	32.9	4.3
3440	47.8	45.5	2.3	.....	.....	.....	.....

Observations made in different parts of the earth tend to show that there exists a certain relation between the yearly average air and ground temperature. At a low elevation, the difference between the air and the ground temperature is only 2 or 3° F., but this difference increases to 5 or 6° for elevations of 12,000 to 14,000 ft.

In most civilized countries, records of the yearly average air temperature at different elevations are available for many years. When not available, or when available for a short time only, at a high elevation, the air temperature can be determined at such elevations by means of the air gradient. The value of the latter one varies also greatly, according to the latitude, longitude and altitude, as observed on several parts of the globe. Selecting the Alpine region for instance, the air gradient is 1° F. for 309 ft. in the south region; 1° F. for 357 ft. in the north region; and 328 and 355 ft. for the eastern and western regions respectively.

In this country, the U. S. Weather Bureau has recorded numerous observations at different elevations, either by means of kites or balloons carrying recording instruments, or by direct observations. For instance, the average air gradient between Pikes Peak, at elevation 14,111 ft., and Colorado Springs, at elevation 6098 ft., was found to be 276 ft. per deg., and 278 ft. between Denver and Corona.

Location of Observation Stations

In selecting the location of the observation station serving the purpose to determine the temperature of the ground, it is

necessary, in order to obtain accurate results, to select an average exposure to the sun's rays, because that part of the mountain which is most exposed to the sun's rays will have a different ground temperature from that of another part less exposed. The following table will give an idea of the variation of the ground temperature for different elevations and exposures as recorded in central Europe.

Elevation above sea level, ft.	North exposure, deg. F.	South exposure, deg. F.	Difference, deg. F.
1650	48.0	.....	.....
3300	45.0	48	3.0
5000	41.0	43	2.0
6500	37.0	38	1.0
8000	33.5	34	0.5
9000	32.0	.....	.....

Method of Making Observations

The rock temperature in a tunnel should be recorded as closely as possible to the heading's face, and before the ventilation has time to exert its cooling effect on the surrounding rock. The bore holes in which the recording instruments are placed should be preferably located at the intersection of the heading's roof and the side wall of the heading, and the holes should be dry. After inserting the thermometer, the hole should be closed with clay or similar material. Several readings should be taken, first at a few hours interval, and then after several days or weeks.

Two methods are used commonly to record the temperature of the ground at the surface: One method consists in driving bore holes say 30 to 50 ft. deep, thus obtaining directly the average ground temperature. This method is expensive, as it is no small task to haul and operate a drilling outfit over a range, especially when parts of the range are snow clad during several months of the year. However, it becomes necessary sometimes to make deep bore holes in order to locate the tunnel portals, and thus direct temperature measurements can be made at little expense.

The second method consists in establishing thermometers in bore holes 5 to 6 ft. deep, located at the surface, at or near the tunnel axis. Readings are then made weekly or monthly, and the average of the readings, for say a year's period, will give fairly reliable information.

When piercing very deeply overlaid tunnels, the range or mountain may be snow clad during several months of the year, and as the readings could be made only under difficulty, maxima and minima, or still better self recording, thermometers can be used. In order to illustrate the variation between air and ground

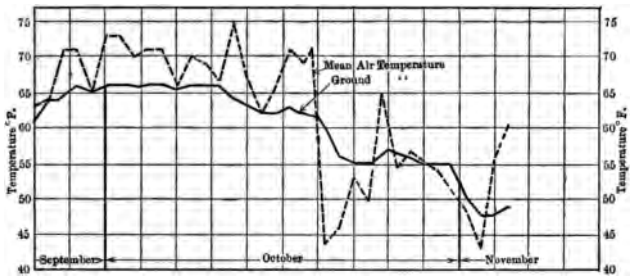


FIG. 127.—Variation in ground temperature as recorded in a bore hole 2 1/2 feet deep.

temperature, the writer made a series of observations in holes varying in depth from 2.5 to 45 ft. Records of the ground temperature at the bottom of the holes, also of the air temperature, were taken daily, or as often as practicable.

From Figs. 127 to 131, giving the plotting of the results of these

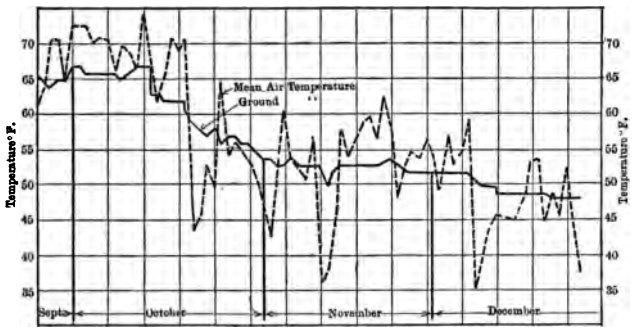


FIG. 128.—Variation in ground temperature as recorded in a bore hole 3 feet deep.

observations, it becomes evident that the deeper the hole in which a thermometer is inserted, the less the variation of the ground temperature is, thus requiring a lesser number of observations. For instance, a thermometer placed in a hole 2.5 ft. deep is subjected not only to daily temperature variations, but also

to hourly variations. A hole 3 ft. deep gives somewhat better results, yet daily variations are still quite perceptible. For monthly observations, holes 4 to 6 ft. deep, if properly sealed, will give fairly satisfactory readings. The observations made in the 16-ft. hole indicate quite a temperature variation within

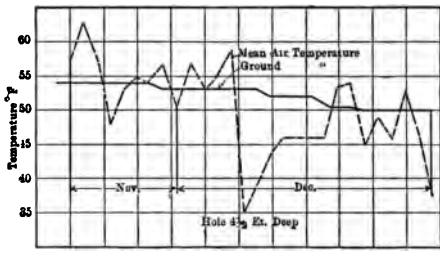


FIG. 129.—Variation in ground temperature as recorded in a bore hole 4 1/2 ft. deep.

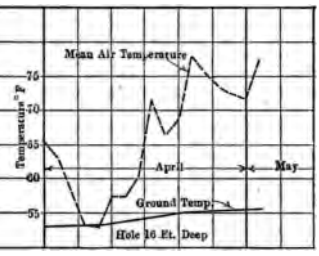


FIG. 130.—Variation in ground temperature as recorded in a bore hole 16 ft. deep.

a relatively short time; this was due to the fact that the location selected for the hole was well exposed to sun rays throughout the day.

Fig. 131 gives the temperature recorded in a hole 45 ft. deep, together with the average air temperature. At this depth the variation of the temperature of the ground is not perceptible.

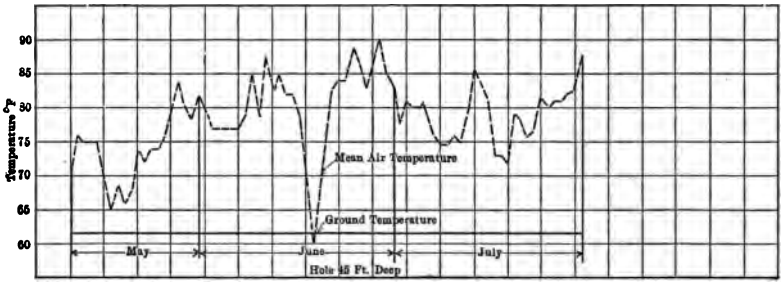


FIG. 131.—Variation in ground temperature as recorded in a bore hole 45 ft. deep.

In the particular case the ground temperature was 61.5° F. and the average yearly air temperature 59° F.

The above examples are for illustration purposes only, for it becomes evide that different results would be obtained at other altitude. and latitudes, also in different kinds of soil.

Wet soils are good heat conductors, and vegetation has a marked influence on the temperature at the ground surface.

A fairly good check on the results thus obtained can be gained by recording the temperature of near-by springs. It is a well-known fact that the temperature of normal springs, that is, of springs that do not travel at very great depth, and that do not contain substances capable to alter their temperature, is about 2 or 3° lower than that of the ground penetrated.

Overlaying Depth to Take into Consideration

It has been stated previously that the shape or profile of a range through which a tunnel is to be driven is of vital importance when determining the value of the geothermic gradient. Mountains or peaks of about 3000 ft. or less in diameter have practically no influence on the gradient. When measuring the depth overlaying the tunnel, the average depth must be

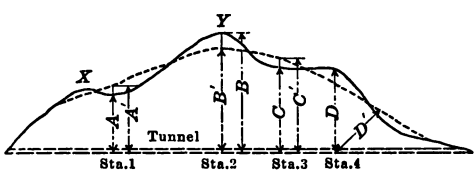


FIG. 132.

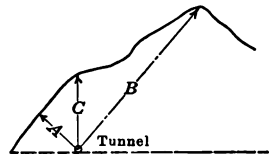


FIG. 133.

FIGS. 132 and 133.—Diagram showing the overlying depth to take into consideration when computing the rock temperature in a deeply overlaid tunnel.

taken into consideration, *i.e.*, the average overlaying depth over a distance, on each side of the tunnel axis, of twice the overlaying depth at that point.

At any point along the tunnel axis, the distance from the latter to the ground surface must be equal or greater than the overlaying depth at that point. This is obvious, for if the distance in a horizontal plane, from the tunnel axis to the ground surface, was less than the overlaying depth, the geothermic gradient and hence the rock temperature would thus be affected.

Fig. 132, showing a longitudinal section through a tunneled range, will best illustrate cases occurring most usually in practice. At station 1, on the tunnel axis, the rock temperature is no more a function of the overlaying depth "A," its value being affected by the two near-by peaks X and Y. The same remark

applies to station 3, while the rock temperature at stations 2 and 4 is affected by a lack of surrounding rather than overlaying masses. The dotted line representing the average overlaying depth has been drawn, and the distances A', B', C' and D' are to be substituted for A, B, C and D.

Fig. 133, illustrating a case liable to occur, shows a cross section through a tunneled range. Here the distance C is to be taken as the average overlaying depth.

Method of Determining the Rock Temperature in the Simplon Tunnel

A geological profile of the Simplon tunnel is illustrated by Fig. 1, together with a distribution of the rock temperature as presented by Prof. G. Niethammer. Owing to the magnitude of the problem involved and to the fact that the rock temperature was expected to play an important part while driving the tunnel, careful observations were made of the ground temperature at the surface above the tunnel axis, and the maximum and minimum ground temperatures were recorded for a whole year. Lamond thermometers were used, located in holes 3.5 to 5 ft. deep. The average ground temperature for the year was then computed and a curve was drawn, giving the ground temperature at any point above the tunnel. This curve is shown below the profile. For instance, at the west portal, at an elevation of 2270 ft. above sea level, the average ground temperature was found to be 43.5° F., while at an elevation of 8840 ft. the ground temperature was but 29.5° F. Geothermic gradients were then assumed for the different materials penetrated and the temperature in the tunnel was then computed.

The maximum rock temperature expected to be encountered in the tunnel is shown by a broken line, above the tunnel profile, while the observed rock temperature is shown by a continuous line. Beginning at the north portal, the two curves are fairly identical; the observed rock temperature then increases rapidly, beyond all expectations, until it reaches 132° F. Two sudden drops in the temperature occurred at points where springs were encountered, one at a spring having a temperature of 120° F. and discharging 11 sec. ft.; the other at a spring having a temperature of 54° F. and discharging 34 sec. ft. In both cases it will be noted that the springs were encountered at the junction of limestone and gneiss or schist.

The rock temperature in the tunnel was recorded in bore holes 4 to 5 ft. deep, before the ventilating air had affected the tunnel walls. The recorded temperature at each kilometer is given in the table below, Col. 1. Col. 2 gives the rock temperature expected, figured by taking into consideration the profile of the mountain only. Col. 3 gives the rock temperature by correcting Col. 2 with respect to the inclination of the strata and the dampness of the rock, while Col. 4 gives the results obtained by correcting Col. 3 with regard to springs or flowing water. It can be noticed that Cols. 1 and 4 agree fairly well, thus showing the possibility of obtaining reliable results for practical purposes.

RECORDED AND COMPUTED ROCK TEMPERATURES IN THE SIMPLON TUNNEL

Kilometer, north portal	Col. 1. Temp. recorded	Col. 2.. Temp. estimated	Col. 3. Corrected for incl. of strata and dampness	Col. 4. Corrected for springs
1	60.8	59.0	57.2	57.2
2	71.6	69.8	68.0	68.0
3	80.6	89.6	82.4	82.4
4	87.8	98.6	93.2	93.2
5	95.0	96.8	91.4	91.4
6	105.8	102.2	102.2	102.2
7	116.6	111.2	111.2	111.2
8	131.0	125.6	127.4	127.4
9	125.6	131.0	129.2	125.6
10	118.4	131.0	125.6	116.6
South portal				
9	114.8	129.2	123.8	113.0
8	102.2	127.4	122.0	107.6
7	102.2	118.4	113.0	107.6
6	100.4	114.8	111.2	98.6
5	78.8	113.0	111.2	77.0
4	77.0	113.0	113.0	78.8
3	89.6	113.0	109.4	93.2
2	93.2	96.8	96.8	95.0
1	77.0	73.4	75.2	75.2

Approximate Method Used to Determine the Rock Temperature in the Proposed Moffat Tunnel, in Colorado

The proposed 6.04-mile tunnel to be driven through the Continental Divide on the Denver, Northwestern & Pacific Railway

in the state of Colorado lies between the boundaries of the meridians 105° 35 min. and 105° 45 min., and the parallels of 39° 50 min. and 39° 55 min. The east and west portals are at elevations of 9190 and 9100 ft. respectively above sea level. The highest track elevation in the tunnel is 9229, and the highest point of the range overlaying the bore is 12,034 ft. That part of the tunnel site located east of the Continental Divide is drained by the south Platte and its tributaries, while the part west of the Divide is drained by tributaries of the Grand River.

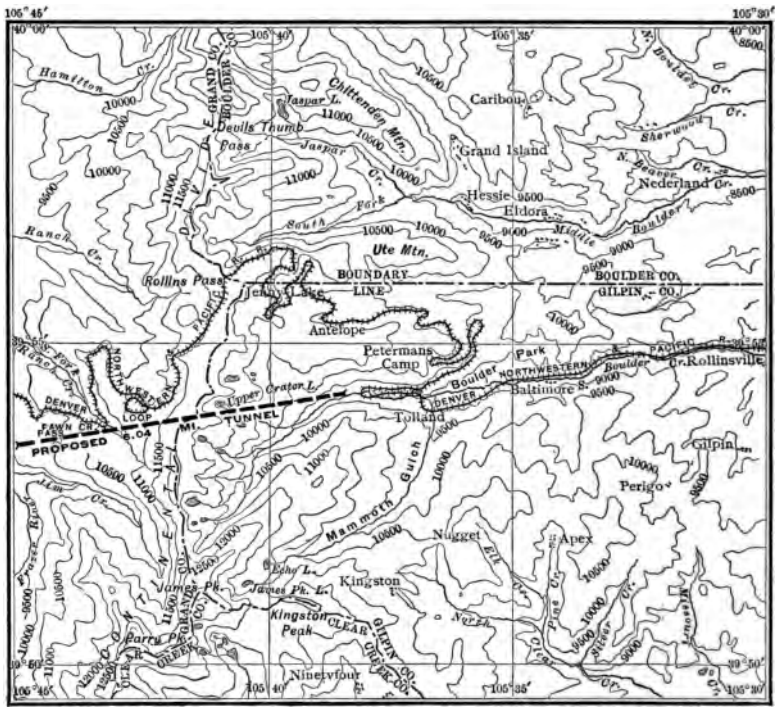


FIG. 134.—Map showing location of proposed Moffat tunnel.

Although there is a marked difference between the climatology of the eastern and western slopes at a low elevation, this difference is far less important at higher elevations, say above 9000 ft. for localities situated on the same parallel. Below the 10,000-ft. level the annual precipitation is somewhat less than 20 in. At higher elevations it may exceed 40 in. At the very highest levels practically all the precipitation is in the

form of snow. A snow fall of over 20 ft. has been observed in a year.

Up to elevation 10,000 ft. the range is still well covered with forests of spruce, aspen and like woods. Still higher, the mountains and peaks are practically bare and practically snow clad during the greatest part of the year.

The contour map shown by Fig. 134 illustrates that part of the range penetrated by the proposed tunnel. Several streams and lakes overlie the tunnel axis, one of which, Lower Crater Lake, lies about 1350 ft. above the proposed bore. It is to be noted that no high peaks lie on either side of the tunnel axis; therefore the longitudinal section taken on the tunnel axis represents very nearly the average section for a distance on each side of the tunnel equal to the overlaying depth at any point considered.

Geological Formation

The rocks forming the range penetrated by the proposed tunnel belong to the Pre-Cambrian age. They are mostly granites, similar to the kind known as the Silver Plum granites, and mica schists of the Idaho Springs formation. Exact data as to the geological formation of the range penetrated is not available; this, however, is of no material importance in the present case, so long as a distinction is made between rocks having no appreciable stratification, as for instance granites and limestones, and stratified rocks such as gneisses, hornblende schists, etc.

Of far more importance is the classification of the rocks belonging to granites, gneisses, limestones and similar varieties, and those having a lesser heat conductivity, such as dry sandstones and more especially mica schists.

In the present case, and for the purpose of comparison, two assumptions have been made: One that the formation is composed of granitoid rocks and the other of mica schists. On account of the near-by lakes and streams overlaying the proposed tunnel on both sides of the Divide, and on account of the vegetation and forests, that part below the 11,000-ft. level is supposed to be composed of relatively wet rocks, while the more steeply inclined regions above the 11,000-ft. level are assumed to be made of dry rocks.

Fig. 135 shows a longitudinal section of the proposed tunnel; the horizontal figures indicate the elevations above sea level

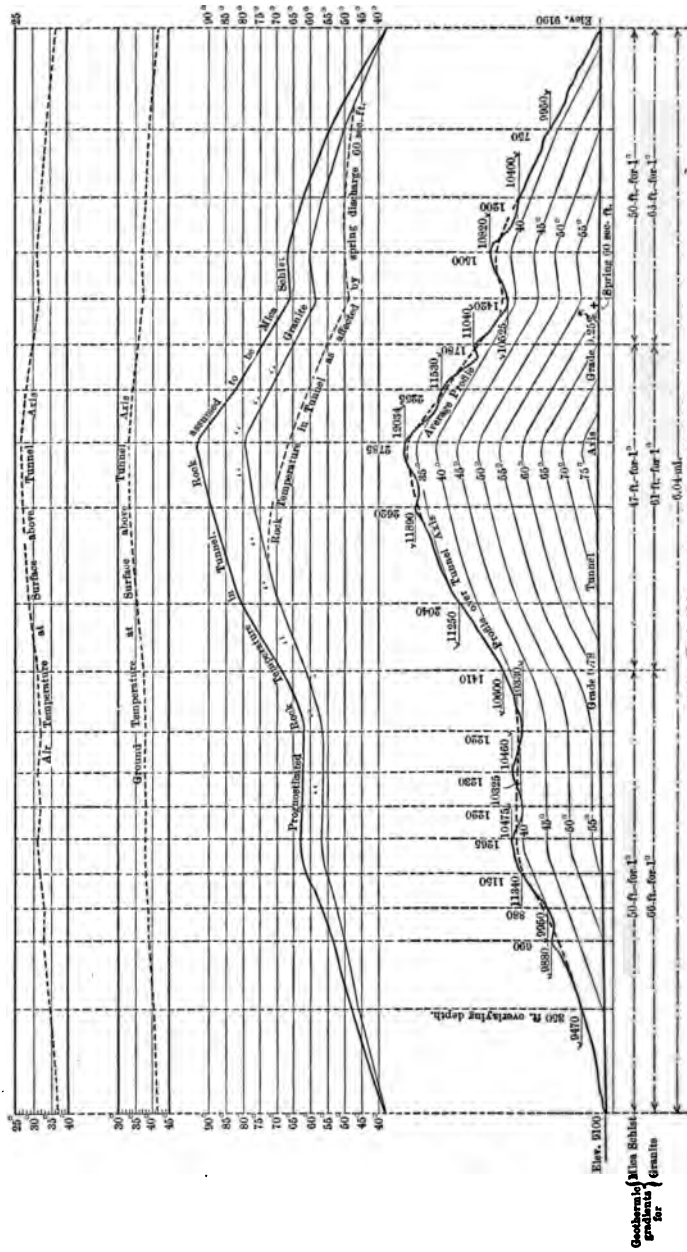


FIG. 135.—Longitudinal section of proposed Moffat tunnel, showing distribution of ground temperature.

at the points considered, and the corresponding vertical figures give the overlaying depths, taken either from the actual surface or from the average profile line.

Computation of the Rock Temperature

The upper curve, in Fig. 135, indicates the average air temperature above the tunnel axis, as obtained from the diagram shown in Fig. 136. The average air temperature was obtained as follows: The yearly average air temperature recorded by the

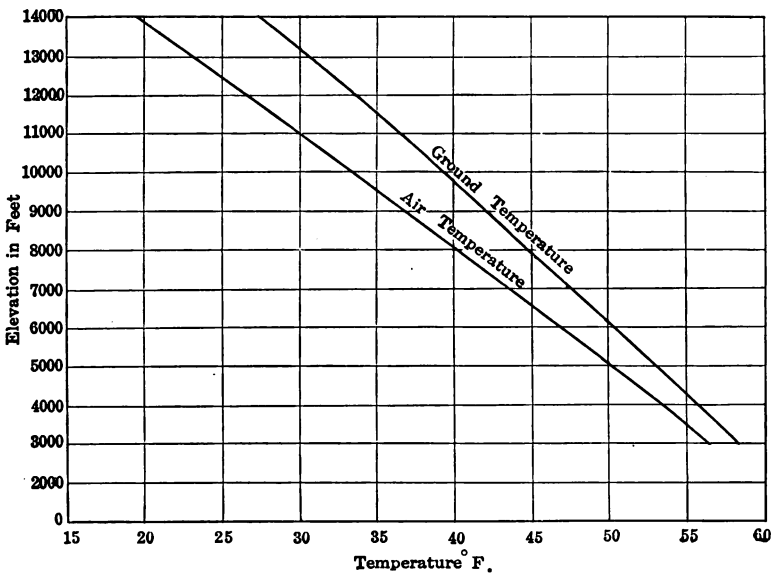


FIG. 136.—Air and ground temperature curves for different elevations above sea level.

U. S. Weather Bureau in the State of Colorado, at forty-six stations for a length of time of 2 to 38 years, and for elevations of 3000 to 14,000 ft. has been plotted. The ground temperature was then plotted with the difference between the air and the ground temperatures at different elevations at several points of the globe.

From the curve showing the air temperature, it will be observed that between elevations of 3000 to 5000 ft., the average air gradient is 334 ft. per deg. F. Between 5000 and 7000 ft. it is 308° F. and between 7000 and 12,000 ft. the gradient is 294

ft. These figures agree fairly well with the values of the average air gradient as determined by the U. S. Weather Bureau between Pikes Peak and Denver. It seems useless to point out that the ground temperature as given, or as might be recorded directly, would vary by a few degrees, according to the exposure of the ground to sun rays, winds, dampness of the ground or its property to assimilate or retain the air temperature. The corresponding average ground temperatures as would be observed in holes 30 to 40 ft. deep below the surface are shown below the upper curve, in Fig. 135.

The rock temperature in the tunnel was then computed using the formulæ:

$$T = t + D/G \text{ or } T = t + d/G$$

Where T represents the temperature of the ground at any point situated D or d ft. below the surface.

t = average ground temperature at the surface.
D = depth below the actual ground surface.
d = the depth below the surface shown by the average profile line.
G = value of the geothermic gradient.

Selecting for instance the point of maximum covering, and making $G = 47$ ft., then

$$T = 33.5 + 2785/47 = 93° \text{ F.}$$

The curves representing the prognosticated rock temperatures in the tunnel have been then plotted as well as the curves showing the distribution of the ground temperature in the mountain range. As will be observed on Fig. 135, the prognosticated rock temperature in the tunnel bears a close relation to the form of the profile of the range penetrated. The effect on the rock temperature in the tunnel caused by an assumed spring is shown by the dotted line; this effect is already noticeable a long distance away from the spouting point of the imaginary spring, though to a lesser extent.

CHAPTER XII

VITIATION OF THE ATMOSPHERE OF LONG TUNNELS

The successful completion of over a dozen long tunnels within the past 15 years, has thrown much light on the ventilation and refrigeration of such tunnels during and after construction, and the progress of medical science together with that of sanitary and mechanical appliances, has made possible for men to work not only a few days, as for instance under the regime of the Cæsars, but for a lifetime, in tunnels subjected to high rock temperature, deadly gases, and a high degree of humidity. In this country, the research work of the U. S. Bureau of Mines in connection with the sampling and testing of mine and tunnel air, also that of inflammable gases and explosives, has added valuable information to that obtained from the driving of long European tunnels.

When exhaled by the human body, air contains about 4.4 parts of carbon dioxide and 15.4 parts of oxygen, as against 0.03 and 20.7 parts, respectively, when pure; thus, air exhaled by men and incidentally by animals, is vitiated by a lack of oxygen and by an increase of carbon dioxide. A certain amount of water vapor is also expelled by exhaling and by the body, the amount depending on the percentage of humidity in the surrounding air.

The amount of carbon dioxide excreted by the human body varies according to the degree of bodily activity; it has been estimated by various authorities that a man of average size gives out 0.6 to 0.7 cu. ft. of carbon dioxide per hr., but a man working hard gives out about 1.2 cu. ft. per hr. For certain practical purposes in connection with the subject treated in this book, it is assumed that a tunnel man working under average conditions excretes 1 cu. ft. of CO_2 per hr.; practically similar conditions prevail with animals, and it has been determined that the amount of CO_2 excreted by a horse or mule is about 8.5 cu. ft. per hr.

Carbon dioxide to the extent of 2°/00 is not injurious to human beings or animals; as a matter of fact, human beings oftentimes

spend several hours daily in rooms containing a larger proportion of CO_2 without experiencing discomfort. Railroad and street cars contain as much as 3°/00 of CO_2; cafes and theaters from 3 to 5°/00; class rooms up to 10°/00. Generally, however, little or no muscular efforts are exercised by people present in the above places; furthermore, their stay is relatively of short duration. In the Simplon tunnel, the amount of CO_2 varied from 0.5 to 7.5°/00 on the south side and from 0.7 to 4.8°/00 on the north side. Driving of the St. Gothard tunnel often proceeded with as much as 10°/00 of carbon dioxide.

The effects of carbon dioxide on men, animals and lights, is quoted by different authorities to be as follows: Up to a content of 2°/00 of CO_2 in air, men and animals are capable of accomplishing hard and continuous work; with 10°/00 of CO_2, men are still able to work under normal conditions without resenting ill effects; in a proportion of 50°/00, human beings are affected and lights burn poorly. Great danger for human beings when air contains 80°/00 of CO_2, and animals die when inhaling air with 130°/00.

The presence of gases has occurred not only in coal mines or coal-bearing strata, traces have been observed, and even large quantities of gases have been encountered in limestone, sandstone and shale formation, both in dry and wet tunnels. These gases consisting chiefly of methane and hydrogen, are produced either by carboniferous, sulphuric or ore deposits, or by the chemical action of water, air or both. Vegetable detritus and remains of dead animals lying on the ground surface are carried by water together with air, into cracks or faults of the earth where a chemical action takes place, and according to the density of these gases and also of the structural formation of the ground, they either rise to the ground surface or penetrate deeper in the ground, hence their appearance in tunnels under construction.

In tunnel work, the daily consumption of some 800 to 1000 lb. of dynamite, contributes largely to the vitiation of the air especially in headings where 50 to 80 lb. of explosives are consumed per round, 6 to 8 blasts being fired in 24 hr. The effect on human beings of the gases of dynamite, consisting chiefly of carbon dioxide, carbon monoxide, nitrogen and to a smaller percentage of hydrogen and methane, is too well known to dwell upon here; poisoning, if not total asphyxiation, caused by in-

haling some of the gases referred to above, has occurred only too frequently in ill-ventilated tunnels, and the engineer is confronted here with the complex problem of the preservation of life with a minimum consumption of time and power. It is generally accepted that the explosion of 1 lb. of dynamite produces 3.4 to 3.6 cu. ft. of carbon dioxide. The burning temperature of nitro-glycerine has been found to be about 5400° F. and it is estimated that the heat given out by the consumption of 1 lb. of dynamite was about 135,000 B.T.U.; yet, from observations made in tunnels of small cross section and in headings, where consumption of explosives was high, it has been found that their influence on the air temperature was very small; due undoubtedly to the rapidity with which their combustion takes place and owing to the specific heat of their gases.

The removing and hauling of excavated and other materials, necessitate the use of a large number of work trains. In the Simplon tunnel for instance, twenty-four trains were usually run per day; in the Loetschberg tunnel, the traffic was still more intense, there being one train every 45 min., that is thirty to thirty-four trains per day. Under similar conditions, it becomes evident that the use of steam locomotives becomes prohibitive, for besides being of no assistance to ventilation, like compressed-air locomotives which in some cases exhaust from 2 to 5 per cent. of the total volume of air introduced in a tunnel, they generate heat, gases and steam. The gases consist chiefly of carbon dioxide, nitrogen, some carbon monoxide and sulphur fumes. Gasolene locomotives have been used quite extensively, and when run properly they do not present such inconveniences as do steam locomotives. Under normal conditions, the gases exhausted consist of nitrogen, carbon dioxide and water vapors. When run in such a way as to cause incomplete combustion, the gases exhausted contain an appreciable amount of carbon monoxide, and in several instances this inconvenience has justified their abandonment.

The methods that serve the purpose of increasing the speed of driving long tunnels involve a large amount of materials to be drilled, blasted and removed, thus producing much dust which naturally also adds to the discomfort of tunnel men. In driving the Loetschberg tunnel, as many as 560 lin. ft. of holes were drilled in 24 hr. in the heading (limestone formation) thus causing some 0.75 cu. ft. of rock to be pulverized every hour, and

when in addition to this, some 500 to 600 cu. yd. of rock were excavated daily, a large amount of dust was forcibly carried away by the powerful ventilation.

The introduction of water-core drills together with the practice of sprinkling the muck before handling it, is a marked improvement in tunnel work. Certain materials when drilled and blasted give out less dust than others: for instance mica schist and in general tough rocks produce less dust than more brittle ones, like granites or limestones. The practice of allaying dust is to be recommended, not only for the sake of the tunnel men's health, but also to reduce the wear of tools and machinery.

The presence of candles, oil and acetylene lamps in a tunnel, affects also to a large extent the degree of purity and the temperature of the air. In long tunnels as many as 300 to 500 lamps are used daily, and a consumption of 400 to 500 lb. of oil or calcium carbide is not unusual. It is estimated that the amount of CO_2 produced by oil and acetylene lamps is about 0.8 and 0.53 cu. ft. per hr. respectively. The use of acetylene lamps is increasing rapidly in connection with tunnel work and they are to be preferred to oil lamps, for in addition to giving out less CO_2, the heat produced is about 7500 B.T.U. per hr., more or less according to the size and make; that is, about one-half only of that given out by oil lamps.

Heat Radiation of Human Beings and Animals, and Humidity of Atmosphere

It is well known that the human body, also that of animals, gives out a certain amount of heat by exhalation and by radiation, the amount depending upon atmospheric conditions and also on the degree of bodily activity; more heat is generated by a man accomplishing hard work than by a man at rest. As the result of various observations, it has been determined that with an air temperature of 70 to 80° F. the amount of heat given out by the human body is 10,000 B.T.U. per hr., that of a horse of average size, 95,000 B.T.U. per hr.

The proportion of humidity in the atmosphere plays an important part in connection with the vitiation and temperature of the air in which tunnel men are called upon to work. Human beings feel best when at an average normal temperature the percentage of humidity is 50 to 60 per cent. Every one has observed that when perspiration does not take place freely, a

feeling of uneasiness is experienced; the greater the humidity, the greater the discomfort. It has been determined that the amount of water perspired by a man at 84° F. and a percentage of humidity of 60, was 4 oz.; with the same temperature and 81 per cent. humidity, the weight of water perspired was only 0.85 oz. Men worked in the St. Gothard tunnel at a temperature of 86° F. and with 100 per cent. humidity; in the Simplon tunnel the percentage of humidity varied from 70 to 98; in the Loetschberg tunnel, the humidity was high, reaching 100 per cent.

Miscellaneous Agencies Affecting the Purity of Tunnel Atmosphere

In addition to carbon dioxide expelled when exhaling, foul or bad odors are excreted by the stomach or the body of men and animals, due either to improper digestion or uncleanliness. Unsanitary conditions, inadequate toilet facilities and poorly drained tunnel stables for horses, are all agencies contributing to the vitiation of the air in tunnels. Where a large quantity of timber is used, decaying or rotting of same together with other agencies of lesser importance, all add to the evils above referred to.

The quantity of carbon dioxide allowed or advocated nowadays in working chambers or zones of long tunnels, varies from 1 to 2°/00, according to the conditions prevailing; under normal conditions, *i.e.*, when the rock temperature and the comsumption of explosives lie within reasonable limits, the last-named figure can be used, but when the rock temperature reaches 90° F. or more, and when 60 to 70 lb. of explosives are consumed per blast in heading work, it is advisable to keep the proportion of CO_2 within 1.5°/00. In the presence of Methane or other explosive gases, it becomes necessary to keep the proportion of CO_2 within 1°/00.

CHAPTER XIII

VENTILATION DURING CONSTRUCTION OF LONG AND DEEP TUNNELS

In driving long tunnels, little reliance can be placed on natural ventilation, for even with a powerful artificial ventilation the seasonal air temperature variations are but little perceptible in a tunnel, save within a relatively short distance from the portal. In the St. Gothard tunnel, for instance, no fluctuation in the air temperature was noticeable 3500 ft. away from the north portal; in the Simplon tunnel, seasonal variations of the air were quite perceptible for a distance of 2000 ft.; but 6000 ft. away from the portal the temperature fluctuations were hardly perceptible. This tends to show that little attention can be paid to external high and low air temperature, and that weight should rather be given to the average yearly temperature.

Although the basic method of ventilating short tunnels varies greatly, it is rather surprising to note that the plenum method has been used almost exclusively in driving some 10 tunnels from 2 to 12 miles long; this is due chiefly to the fact that conditions not met with in driving short tunnels are encountered in driving long ones. For instance, the driving methods used in connection with the last-named tunnels necessitated that fresh air should be distributed along various working sections of the tunnel, and in order to cool the air in the bore within a practicable limit, fresh air has to be supplied to the heading or other points within a very short time after leaving the fan or blower so as not to be subjected to heating when coming in contact with the walls of the bore, oftentimes warmer by many degrees than the air supply.

The necessity also of using for mechanical, construction and economical reasons, a primary ventilating system consisting of fans located at the tunnel portal, and of blowers and injectors for the ventilation of the heading are some of the reasons for giving preference to the plenum method of ventilation during construction. Yet a combination of the plenum and vacuum methods have been used in a few isolated cases, or when the

portal ventilators were to be part of the system to be used in connection with the permanent ventilation after construction.

Quantity of Air Necessary for Ventilation during Construction

This is by no means a matter of guess, as is often believed and done; erroneous assumptions have led to a lack of adequate ventilation in a few instances and to a waste of power in others. The amount of air necessary to overcome the evils caused by the agencies referred to in a previous chapter can be based: 1. On the amount of carbon dioxide excreted or produced by men, animals and lights. 2. On the amount of CO_2 produced by the consumption of explosives. 3. On the heat generated by the presence of men, animals and lights. 4. On the heat occasioned by the temperature of the rock penetrated. 5. On the gases liable to be encountered during the driving period. 6. On miscellaneous agencies affecting the condition of air. The vitiation of tunnel air referred to in items 1 to 4 inclusive can be estimated with reasonable accuracy for all practical purposes, but the conditions brought on by agencies such as are referred to in items 5 and 6 can only be provided for by making a reasonable allowance for contingencies, and the judgment of the engineer, together with that of the geologist, should govern in this matter.

For nearly all practical purposes, the amount of air necessary for the ventilation of a long tunnel during construction, exclusive of that for the ventilation of the heading, can be expressed by the formula:

$$Q = \frac{A\,(1 - B)}{B - D} - C \qquad (1)$$

Where Q = amount of air (in cu. ft.) introduced into the tunnel in 24 hr.

A = Total amount of carbon dioxide (in cubic feet) given out in 24 hr., by men, animals, lights and explosives.

B = amount of carbon dioxide allowed in tunnel air.

C = cubic contents (in cubic feet) of the tunnel section in which crews are working.

D = cubic contents (in cubic feet) of carbon dioxide in 1 cu. ft. of air, generally taken as 0.0004 cu. ft.

Example: In a tunnel driven under fair conditions, three shifts of 300 men each, with acetylene lamps and 4 horses are employed, and 500 lb. of explosives are consumed per 24 hr. The tunnel crews are spaced over a length of 6000 ft., and the tunnel has a cross sectional area of 400 sq. ft. Carbon dioxide is not to exceed 2 parts in 1000.

Then in formula 1, A equals 13,582 cu.ft.; $B = 0.002$; $C =$ 2,400,000 cu. ft.; $D = 0.0004$, and Q is found to be 6,087,500 cu. ft. per 24 hr. or 4320 cu. ft. per min.

Should now the rock temperature be high and the consumption of explosives very considerable, B should be made 0.00175 or even 0.0015. Using these figures in the above example would make Q equal to 5330 and 6840 cu. ft. respectively.

Formula 1 if used to determine the amount of air necessary for heading ventilation would give results altogether too low to meet the requirements of heading work. In driving long tunnels the field of operation is spread over a large zone, extending over a distance of several thousand feet, and blasting occurs at several points, as against one face only in heading work; also the mining crews, timbermen, masons, etc., are distributed in small groups of 10 to 50 men, in a room of large cubic contents. In a heading altogether different conditions prevail; here we have some 20 to 25 men with lights, cramped in a room 60 to 80 sq. ft. in cross section, and 100 to 150 ft. long; the consumption of explosives varies from 50 to 90 lb. per blast, according to the material penetrated, and when 6 to 8 blasts are fired daily, as little time as possible can be lost after firing so as to enable the mining crews to resume their work. According to the efficiency of heading ventilation, the time lost or spent idly by the men, waiting for fumes to clear off after a blast, varies from 15 min. to 1 hr., 30 to 40 min. being a fair average. In such cases, the amount of air necessary for adequate ventilation can not be based on the amount of carbon dioxide excreted by men, animals and lights, but chiefly upon the consumption of explosives, in one blast; also on the rock temperature and the gases encountered, if any.

The following formula, if used with judgment, will be found of assistance in determining the amount of air to be forced into a heading:

$$Q = \frac{\dfrac{A(1 - B)}{B - D} - C}{T} \qquad (2)$$

Where Q = amount of air, in cu. ft. introduced in the heading per min.

A = amount of carbon dioxide, in cu. ft. produced by the consumption of explosives in one blast.

B = amount of carbon dioxide specified for the air in the heading at the end of time T.

C = contents of heading, in cu. ft.

D = 0.0004.

T = time from explosion of round until resumption of work in heading, in min.

Example: In a heading 7 by 10 ft. in cross section, and 300 ft. long, the consumption of dynamite per blast is 60 lb. The men are to work in an atmosphere containing not more than 0.002 of carbon dioxide, 20 min. after firing a blast. Then, in formula 2, $A = 210$; $B = 0.002$; $C = 21{,}000$; $D = 0.0004$, $T = 20$, and Q is found to be equal to 5500 cu. ft. According to the conditions prevailing, Q can be made larger or smaller, by giving B or T different values.

The amount of air to be forced by, and the capacity of the ventilators, depends to a large extent on the type of drills used in driving a bore. The Mont Cenis and St. Gothard tunnels were driven solely with the assistance of the ventilation produced by the exhaust of air drills; the ventilation thus available was poor, however, and insufficient in many instances; yet these bores were computed without other means of ventilation. The rock temperature in these tunnels was not very excessive, and the driving progress very slow. On the other hand, the capacity of the ventilating plant of the Simplon tunnel was remarkable for its magnitude, necessitated by a high rock temperature and by the total absence of air drills, water drills being used in the heading, and hand ones in the enlargement. The use of air drills in connection with the driving of recent tunnels, besides enabling more progress to be made at a lesser cost, has become a valuable auxiliary to tunnel ventilation.

In the Loetschberg tunnel, from four to six large Ingersoll Rand drills and as many as fifteen hammer air drills were used. In the Hauenstein tunnel there were as many as forty drills at one end of the bore.

The following table gives the amount of air introduced into the south side of the Loetschberg tunnel by the ventilating system, together with that of drills and locomotives.

Date	Air exhausted by drills, cu. m.	Per cent. of total	Air exhausted by locomotives, cu. m.	Per cent. of total	Air exhausted by vent., cu. m.	Per cent. of total
June, 1909.....	105,680	7.0	18,720	1.2	1,382,400	91.8
Sept., 1909.....	102,000	7.2	19,000	1.3	1,300,000	91.5
Dec., 1909.....	132,000	18.8	26,000	3.7	542,000	77.5
Mar., 1910.....	132,000	18.8	30,000	4.3	538,000	76.9
June, 1910.....	132,000	22.2	32,000	5.4	430,000	72.4
Sept., 1910.....	132,000	14.1	23,400	2.5	777,600	83.5

Thus, 7 to 22 per cent. of the total amount of air introduced into the tunnel was exhausted from the drills, while that introduced by the air locomotives was as high as 5.4 per cent. of the total. As a matter of fact, later on, 50 per cent. of the air introduced in the bore was exhausted from the drills. This fact is to be kept in sight, for it demonstrates in a most convincing way that, instead of using a large amount of power for the ventilation alone, it is more economical to use power that will operate drills first, and then be still of utility for ventilating purposes.

It has been found that, for low rock temperatures, up to say 90° F. the air temperature in a tunnel or heading is 5 to 7° F. higher than the rock temperature, and also that the air temperature reached a maximum during mucking, as shown in Figs. 137 to 140. At this very moment, that is just after firing a blast, the drillers are busy setting up their drills, the muckers are loading the blasted material into cars as rapidly as possible, thus the necessity of doing away with the fumes of explosives in a minimum lapse of time.

Refrigeration of Tunnels during Construction

It is beyond the scope of this book to go into lengthy details pertaining to the refrigeration of long tunnels during construction; however, let it be pointed out briefly that the cooling of air by air is only possible or economical within a certain limit; in the Simplon tunnel, for instance, this limit was reached when the air temperature in the tunnel was 100° F.

In order to cool the tunnel air by the introduction of fresh air, when the rock temperature is high, it would be necessary to force in a large amount of cool air from outside; but, as the size of ventilating pipes or conduits is limited to certain practical dimensions, depending on the room available, the velocity of

the air conveyed by these would soon reach too high a velocity; the friction would increase rapidly, thus generate heat, and the air would reach its destination at too high a temperature to be effective for refrigerating purposes. Should the fresh air supply be a few degrees warmer than the rock temperature when reaching the heading, it would have little cooling effect, if any, on the air temperature; fortunately, in most cases, the ventilating air

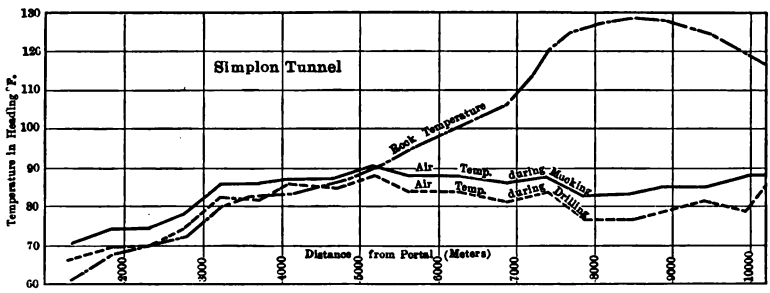


FIG. 137.—Curves giving air and rock temperature in Simplon tunnel.

has a lower temperature than that of the rock. With a high rock temperature, of say 100° F. or more, other means of refrigeration have to be resorted to.

As it is not proposed to describe here the methods that have been or are being used to ventilate long tunnels in each case, the reader is referred to the table below, giving the characteristic features pertaining to the ventilation of twelve tunnels 12,000 to 65,000 ft. long; yet, it is interesting to review the methods

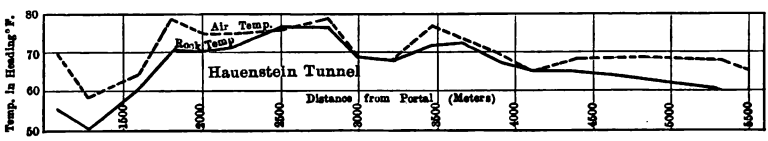


FIG. 138.—Curves giving air and rock temperature in Hauenstein tunnel.

advocated or used at various epochs of modern tunnel construction:

The experience gained in driving the Mont Cenis and St. Gothard tunnels had demonstrated clearly the inconvenience caused by inadequate ventilation, and when driving of the Arlberg tunnel was started, an elaborate ventilating plant was provided at each portal; on the east side of the bore, where air drills

were used, the capacity of the plant was 5300 cu. ft. per min. and on the west side where water drills were used 6350 cu. ft. Iron pipes served as means of air conveyance. Later on, the capacity of both systems was increased to 12,600 cu. ft. per min.

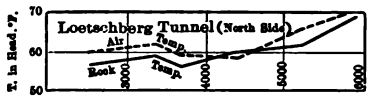


FIG. 139.—Curves giving air and rock temperature in Loetschberg tunnel, north side.

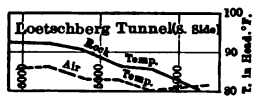


FIG. 140.—Curves giving air and rock temperature in Loetschberg tunnel, south side.

No.	Name of tunnel	Length of tunnel	Overlaying depth	Rock temp.	Air temp.	Explosive consumption per 24 hr.	Air for ventilation per 24 hr.	Power consumption
		Ft.	Ft.	Deg. F.	Deg. F.	Lb.	Cu. ft.	H.P.
1	Simplon	65,042	7,100	130	96	1,100	76,000	400
2	St. Gothard	49,147	5,570	87	87	660	4,200	.....
3	Loetschberg	47,680	5,200	94	86	1,000	34,000	350
4	Mt. Cenis	42,142	5,430	85	86	440	2,100	.....
5	Arlberg	33,600	2,360	65	...	770	12,600	250
6	Ricken	28,200	1,740	78	77	500	8,400	200
7	Granges	28,093	2,880	72	70	600	8,000	150
8	Arthur Pass	28,060	1,100[1]	...	...	500	3,000	55
9	Tauern	27,965	5,150	74	...	450	12,360	420
10	Albula	19,240	2,370	59	...	.....	2,000	30
11	Bosruck	15,630	3,530	48	...	500	12,360	280
12	Weissenstein	12,136	1,640	55	55	300[1]	6,000[1]	.....

[1] Denote approximate figures.

In 1891, when the Simplon project was considered anew, it was estimated that, having regard to the high rock temperature to be expected (107° F.), an adequate system of ventilation would be required, and the following plan of construction was advocated (Fig. 141). From the north portal to about half way between portals, the tunnel was to have a cross section accommodating two tracks; the bore would then branch off in two single-track tunnels extending to the south portal and connected at intervals with cross galleries. During construction, on the south side, a ventilating plant at the portal of tunnel 2 was to exhaust the vitiated atmosphere of tunnel 1 through the cross galleries; tunnel No. 2 was to be closed at the portal by a bulkhead *E*. Thus, fresh air would rush in at *C* during construction

No.	Type of haulage	Size of ventilating pipes		Type of drill	Type of lights	Number of men per 24 hr.
		Heading	Enlargement			
1	Air loc. Air loc.	8 in.	15.75 in.	Water	Acet.	800
2	Steam loc.	None	None	Air	Oil	400
3	Air loc. Horses	17.75 in.	47.25 in.	Air	Acet.	1000
4	Steam Horses	None E. 19.75 in.	None	Air E. water	Oil	250
5	Steam Horses	W. 15.75 in.	.....	W. water	Oil Oil	700
6	Steam	13.8 in.	31.5 in.	Air	Acet.	400
7	Air loc. Gasolene	.....	23.0 in	Air	Acet. Acet.	550
8	Electric Electric	9 in.	16.0 in.	Air	Electric Acet.	150[1]
9	Benzene	19.7 in.	31.5 in.	Water	Electric	400[1]
10	Horses	.....	.....	Water	Oil	.....
11	Steam	11.8 in.	19.4 in.	Air	Gasolene	300[1]
12	.....	13.75 in.	23.6 in.	Air	Acet.	500

[1] Denote approximate figures.

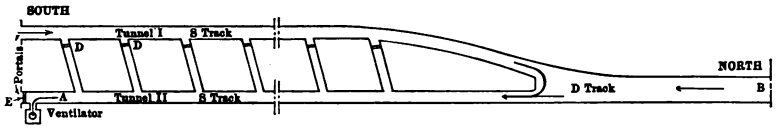


FIG. 141.—Sketch showing proposed method of ventilating the Simplon tunnel.

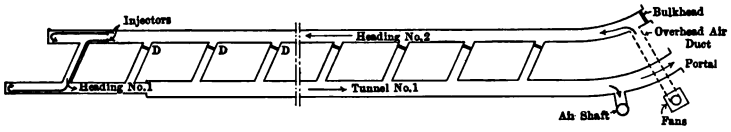


FIG. 142.—Sketch showing method adopted to ventilate the Simplon tunnel.

and also at *B* after completion of the tunnel; during the driving period the cross galleries, except that nearest to the heading, were to be closed by bulkheads *D*. On the north side, the ventilation was to be provided by forcing in air from the portal, through a 31.5-in. diameter pipe. It was estimated that, theoretically, 0.56 cu. ft. of air per sec. and per H.P. could be forced in through the ventilating pipe, and 9.5 cu. ft. per sec.

and per H.P. through the double tunnel system on the south side. Thus, for equal power consumption, the intensity of the ventilation would be 17 times greater with the double heading system than with the ventilating pipe. Later on it was decided to drive two single-track bores between the end portals.

Ventilation and Refrigeration of the Simplon Tunnel as Actually Built

The primary ventilating plant consisted of two fans 12.3 ft. in diameter, each driven by a 200-H.P. hydraulic turbine, located at the portals, as shown by Fig. 142. When running in parallel, the capacity of the fans was 105,800 cu. ft. per min. at 5.7 oz. water pressure; air was forced into heading No. 2 and exhausted through tunnel No. 1, being conveyed from one bore to the other through the gallery nearest to the heading's face, and the other closed by a bulkhead *D*.

In order to ventilate the top heading, a sailcloth curtain, as shown in Fig. 143, was

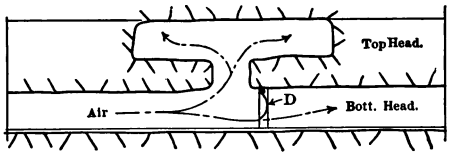


FIG. 143.—Method adopted to ventilate the top heading, Simplon tunnel.

provided at each upraise, to deflect the air current upward. In the very hot sections, however, the ventilation of the top heading became so inadequate that, instead of driving a top heading, it became necessary to stope down the rock overlaying the bottom heading, on a timber platform (Fig. 144). This method of ventilation was found to be more effective, the air being thus given a better circulation through both the top and bottom headings.

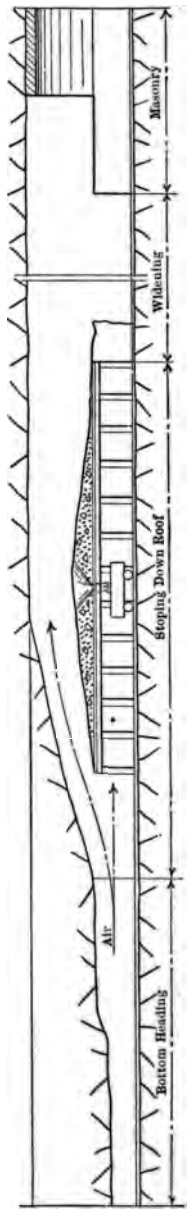


FIG. 144.—Method adopted for the ventilation of the stoping sections, Simplon tunnel.

The secondary ventilation consisted of water injectors, Fig. 145, installed at the transverse gallery next to the heading's face. Power-driven blowers were used also to some extent, but with little success. The intake end of the injectors was located in heading No. 2 and one pipe conveyed air to each heading. Each injector consisted of a nozzle through which 3.8 cu. ft. of water was discharged per min., at 1100 lb. pressure and 280 ft. velocity per sec.; about 2100 cu. ft. of air was thus forced per

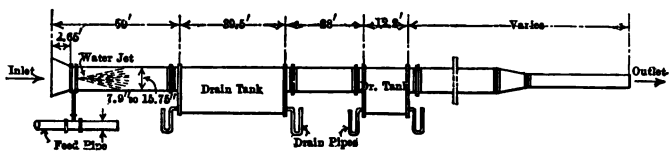


FIG. 145.—Water injector used for the secondary ventilation in the Simplon tunnel.

min., at 5.6 oz. pressure, through 300 ft. of 15.7- and 8-in. diameter pipe; as many as four injectors were installed on one conduit 1300 ft. long.

Owing to the increase in temperature, the primary and secondary ventilating systems soon became inadequate, and the following methods of refrigeration were resorted to: In heading No. 2, twenty-one water sprays, Fig. 146, were installed, forming

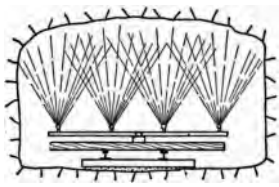


FIG. 146.—First type of water sprays used in the Simplon tunnel.

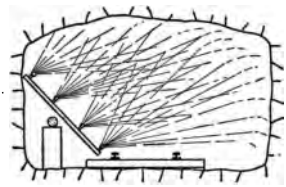


FIG. 147.—Second type of water sprays used in the Simplon tunnel.

a water curtain 65 ft. deep, through which passed the air forced in by the portal fans; the air thus cooled off, but containing much humidity, was forced through wire screens located in front of the sprays. This system, although very effective, was a serious hindrance to traffic, and it was superseded by that illustrated in Fig. 147. The above appliances enabled air to be cooled by about 17° F., the temperature of water used for spraying purposes varying from 39 to 62° F., according to the season. In

order to cool the air conveyed by the ventilating pipes in the heading, ice cars were branched on the ventilation pipes, as shown in Fig. 148 and air forced through these. Each car contained 513 vertical tubes 1-½ in. diameter, 31 in. long, presenting to the ventilating air a surface of 540 sq. ft. This cooling system necessitated twelve ice cars per day; after 5 months' use it was abandoned altogether, being too costly and very cumbersome.

In addition to the above refrigerating systems, perforated pipes located at intervals in the tunnel or heading served the purpose of sprinkling the walls of the bore with cold water.

From observations it has been determined that in heading No. 1 for instance, when the rock temperature was highest (130° F.)

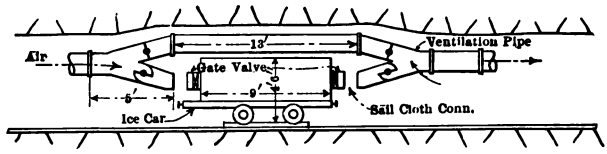


FIG. 148.—Ice car connected with the ventilation pipe in the heading of the Simplon tunnel.

the cooling effect due to air and water supplied for this purpose was as follows: During drilling, 11.6 B.T.U. were absorbed per sq. ft. of rock surface and per hr., and during mucking 6.4 B.T.U. per sq. ft. per hr.

Ventilation of the Loetschberg Tunnel

The system of ventilation used on the south side of this bore will be described only, that on the north side being similar, although somewhat less elaborate.

During the first construction period, that is until the tunnel had reached a length of about 11,500 ft., the ventilating plant consisted of two Capell blowers, located at the portal, Fig. 149, and having a total capacity of 4200 cu. ft. per min. at 10.8 oz. pressure. Air was forced through wrought-iron pipes 47.3 in. diameter at the blower outlet and 17.7 in. in the heading. When the pipes had reached a length of 7300 ft., two water injectors were installed on the pipes, this system being used until the tunnel reached a length of 11,500 ft., and as many as four injectors were used on the air conduit. Soon after the ventilating plant, which

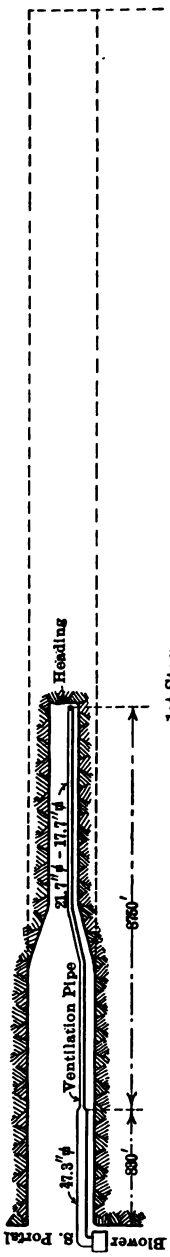


FIG. 149.—Layout of ventilating system, Loetschberg tunnel.

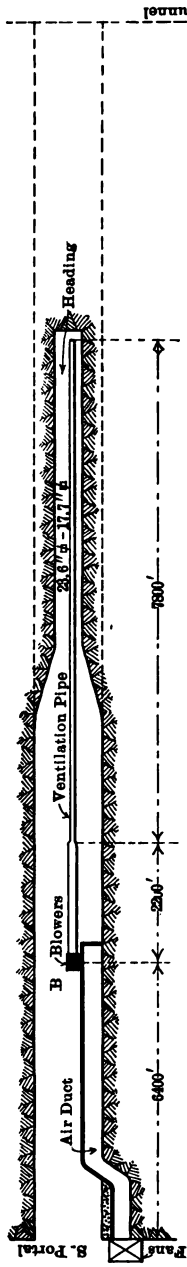


FIG. 151.—Layout of ventilating system, Loetschberg tunnel.

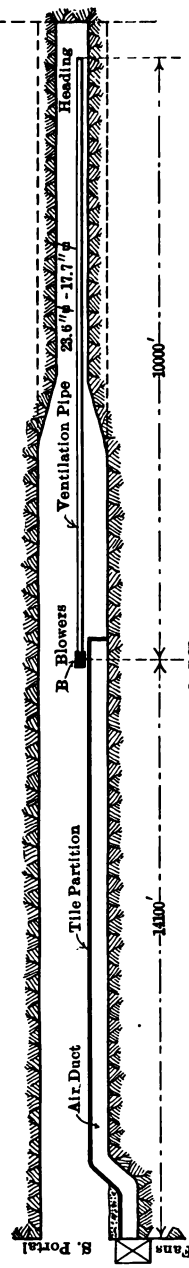


FIG. 152.—Layout of ventilating system, Loetschberg tunnel.

was to be used during the operation of the tunnel, was put in operation; it consisted of two fans 11.5 ft. diameter driven by 175 H.P. electric motors, and having a total capacity of 106,000 cu. ft. per min. at 5.7 oz. pressure. Air was conveyed in the tunnel through a duct of 68 sq. ft. area, Fig. 150. The secondary ventilation consisted of blowers "*B*" of 100 cu. ft. capacity per sec., taking air from the main ventilation duct and forcing it through the heading at 3.8 oz. pressure, through pipes varying in diameter from 47.3 to 17.7 in. as shown in Figs. 151 and 152. At intervals water injectors were provided on the pipe, and, as work progressed, the masonry duct and the secondary ventilating plant, the latter being carried on trucks, Fig. 153, were moved forward. According to the rock temperature, as many as three electrically driven blowers were provided on the ventilating pipe. When available, large quantities of snow were also introduced into the tunnel. During construction, the primary ventilation was found to be too high a capacity, and their supply was reduced to 10,000 cu. ft. per min.

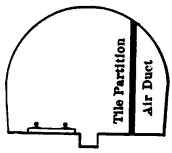


FIG. 150.—Sketch showing location of air duct for primary ventilation, in the Loetschberg tunnel.

Conclusions

For tunnels 25,000 to 35,000 ft. long, a ventilating system, consisting of fans at the portals, forcing in a large quantity of air at a low pressure, and of power-driven blowers and water injectors, for the ventilation of the heading, will be found amply adequate in most instances; for, let it be pointed out here, that there exist a relation between the length and the mass, or height of material overlaying a bore; one can hardly conceive a short tunnel very deeply overlaid.

For double-track tunnels, 40,000 to 50,000 ft. long, when the rock temperature is not expected to exceed 100° F. by many degrees, a duct system similar to that used in the Loetschberg tunnel will prove ample and feasible in most cases. For longer tunnels, where a high rock temperature may be encountered, the double bore system, consisting either of two single-track tunnels, or of a double-track tunnel with an auxiliary bore of smaller dimension, driven parallel to and connected at intervals by cross galleries with the main bore, may have to be resorted to.

FIG. 153.—Removable secondary ventilating plant, Loetschberg tunnel.

FIG. 154.—Permanent ventilating plant at the north portal of the Loetschberg tunnel. (*Facing page* 162.)

THE NEW YORK
PUBLIC LIBRARY
ASTOR, LENOX
TILDEN FOUNDATIONS

THE NEW YORK
PUBLIC LIBRARY
ASTOR, LENOX
TILDEN FOUNDATIONS

CHAPTER XIV

TUNNELS DRIVEN THROUGH SOFT MATERIALS

Tunnels under this classification are a small proportion of bores driven in general. High mountains are usually of rock formation, therefore, tunnels driven through soft materials are little overlaid, relatively speaking, and of small or moderate length only. They may be driven in connection with longer tunnels driven through rock, forming the approach of such tunnels, or else, independently, under low hills of late formation.

Nevertheless, they involve often complicated and costly driving, timbering and lining methods, and the contingencies pertaining to this class of tunneling are numerous. Sometimes soft or plastic rock is encountered in driving deep tunnels, as for instance, in the Simplon and Karawanken tunnels, but such cases are remote, and have been discussed in a previous chapter.

In Europe, the German, Belgian and English, and more recently the Austrian method, have been used in driving tunnels through soft rocks. In local cases also the so-called English and Italian methods.

In this country, chiefly the American method has been used, although the modified German method has been applied in connection with the Baltimore Belt Line tunnel, and the English-American method has been used in driving the Musconnetcong and Hoosac tunnels.

Among the chief characteristic features pertaining to the methods referred to above, mention should be made of the driving method, which is essentially a drift method; the timbering, involving a large amount of timber, and the method of lining which is carried on piece-meal and which, thereby, is very costly.

For these reasons, and owing to the constant increase in wages on both continents, most of these methods have been abandoned more or less, and they will be reviewed here but briefly.

Also, since the introduction of modern excavating machinery such as steam shovels, excavators of various types, and of cable-

ways, there is a tendency among builders to increase the depth of road and railroad open cuts, thus doing away with short tunnels, little overlaid.

German Method

This method was originated in France, but it found a broad application in Germany and Austria where it has been used in

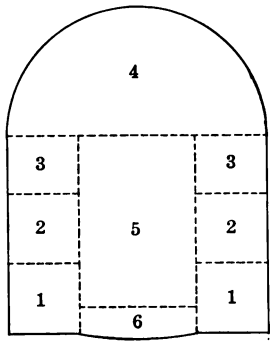


FIG. 155.

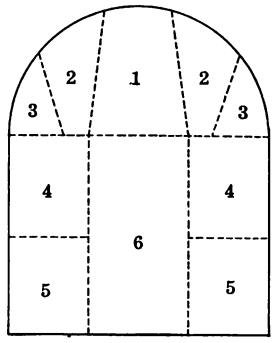


FIG. 156.

FIGS. 155 and 156.—Sequence of excavation, German method.

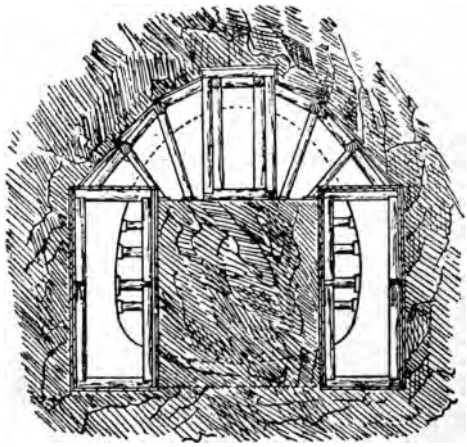


FIG. 157.—Method of excavating and timbering, German method.

connection with driving the Königsdorfer tunnel in 1837, the Triebitzer tunnel in 1842, the Weberkogelt tunnel, and the Czernitzer tunnel, etc.

The method was subsequently modified as shown in Figs. 155

and 156. The top heading method is used chiefly in firm material, while that with bottom drifts in loose materials. The method of timbering is illustrated in Fig. 157. The side bottom drifts are timbered first when first driven, and in both cases, the masonry lining is laid beginning with the side-wall footings and finishing with the invert.

This method of tunneling has serious disadvantages which are very apparent when driving single-track bores, and tunnels of smaller dimension. The center core becomes a serious hindrance to driving, draining and lining, and especially to hauling. Little room is made available for ventilation, and when the center core is removed, there is always a possibility for side or horizontal pressure to cause disturbance in the lining, until the invert is laid.

Belgian Method

The Belgian method, also called French method, consists in driving first a top-heading of small dimension, and then in

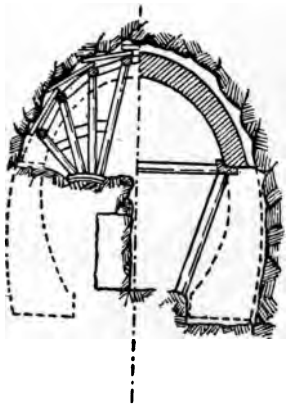


FIG. 158.

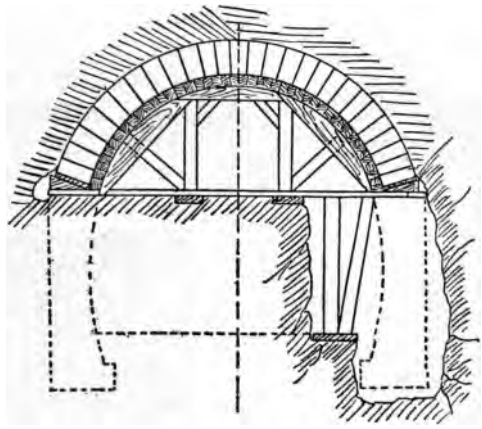


FIG. 159.

FIGS. 158 and 159.—Method of excavating, timbering and lining, Belgian method.

enlarging it to the springing lines of the arch. As driving goes on the heading is timbered, and radial struts are provided, as shown in Fig. 158, until the roof is fully timbered. The longitudinal method of strutting, with the poling boards running transversely of the tunnel, is usually used in connection with this

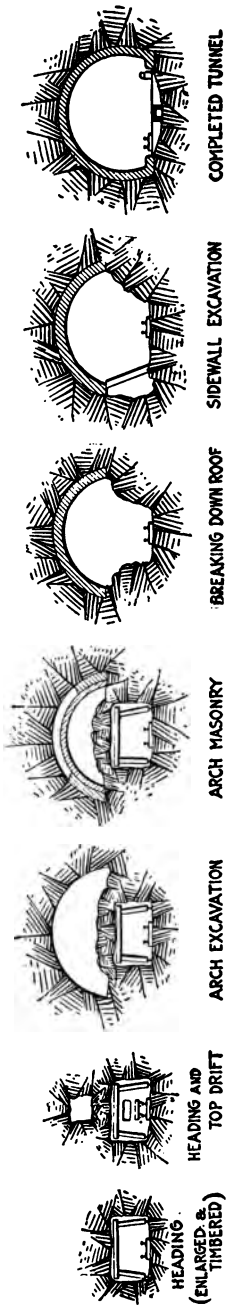


FIG. 160.—Successive sections of Mont d'Or tunnel, showing stages of construction.

method of tunneling. The bench is then excavated by removing a center core, or one-third of the bench, beginning on one side first, as illustrated in Figs. 158 and 159.

The operations of driving, timbering and lining are carried on over a length varying with the cohesion of the material penetrated and the intensity of the pressure. In loose and heavy material, the working sections are kept closer together than in more or less self-sustaining material.

A modified form of the Belgian system is illustrated in Fig. 160; it consists in driving a bottom heading first, and then a top heading, from upraises spaced at intervals. The top heading is then enlarged the full width of the arch, and the arch masonry is completed. The side walls are then excavated, as shown in Fig. 160, the arch masonry is underpinned and thus the side walls are completed. This method has been used recently in connection with the 20,021-ft. double-track Mont d'Or tunnel, driven through limestone and marl, and remarkably good progress has been attained.

The original Belgian method has been used in driving the St. Gothard and Bosruck tunnels.

Another modification of the Belgian system was used in driving the Roosebeck tunnel in Germany; the method consisted in driving the top heading first and then the bench in three half subbenches, carrying the side walls of the lining from the arch springing down to the footings on the tunnel grade. The advantages of the Belgian method lie in the possibility of rapid driving, sim-

ultaneously with carrying the timbering and lining operations. The arch timbering is not subjected to compression for any great length of time, as the arch masonry is laid first.

The chief disadvantage is that the arch has to be underpinned, and, in loose material, there is danger of the underpinning posts to sink in the ground, thus causing the arch to settle. The haulage operations are somewhat complicated by the necessity of shifting the tracks, as work proceeds, from one level to another.

English Method

This method of tunneling has been used quite extensively in Europe and to a lesser extent in this country. The first Hauenstein tunnel, in Switzerland, was driven with this method, and the Hoosac, Musconetcong, Baltimore and other tunnels in the U. S. were also driven with the English method, somewhat modified to suit local conditions.

The success of the method depends to a large extent on the material penetrated, firm material being decidedly in its favor. Therefore, the use of the method is somewhat limited.

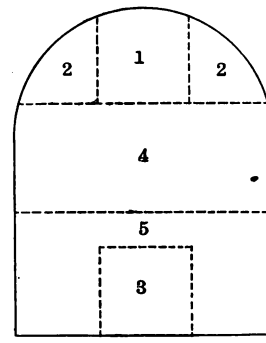


FIG. 161.—Sequence of excavation, English method.

The sequence of excavation is illustrated by Fig. 161. Usually, a heading is driven, either at the top or the bottom of the section and then widened over a length of 10 to 20 ft., according to the material encountered. Section 1 is widened to full width, temporary struts carrying longitudinal bars with poling boards being provided to hold the roof. A transverse strut A, shown in Fig. 162, is then provided and permanent struts or posts are substituted to the temporary ones. The same procedure continues until the full bore is excavated. Inclined posts are provided to hold the set upright.

When the masonry has been carried close to the set, the latter is taken down, and the excavation is carried forward, the crown bars resting on the completed masonry being pulled out one by one.

The masonry lining is built in sections equal to the progress made during one cycle of excavation, the invert being laid first, then the side walls and finally the arch.

It will be realized that this method of tunneling is rather slow, as work on the excavation, timbering and lining is not carried on simultaneously. Furthermore, it is a rather risky matter to carry on a bore, full face, especially in materials of variable cohesion.

A large amount of packing is required to fill the voids left by removing the crown bars.

The chief advantage of the method lies in the possibility of carrying the masonry from top to bottom, continuously, with ample elbow room for the masons and carpenters. Ample room is also provided to lay the tracks for haulage purposes.

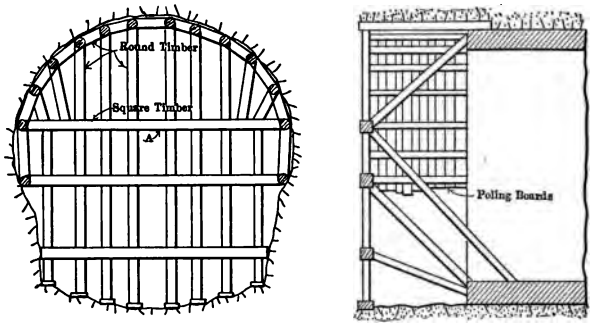


FIG. 162.—Timbering system, English method.

Austrian Method

This method, used first in 1837, has outlived and lately superseded other tunneling methods in Europe. It has been improved and used in connection with driving tunnels in loose and solid materials, both in short and long tunnels. The method embodies several features of the methods previously described. For instance, the section is excavated entirely, before the lining is started, and the latter is carried on from the foundations up, as is done when using the English method.

The method of excavation is illustrated in Fig. 163. A bottom heading is driven first, for some distance, same being short in heavy and unstable material, and several hundred feet long in solid material. A top heading is driven from the face, and in long tunnels also from the bottom heading, at intervals, through upraises, thus giving several points of attack.

The top heading is then widened out and timbered, as shown

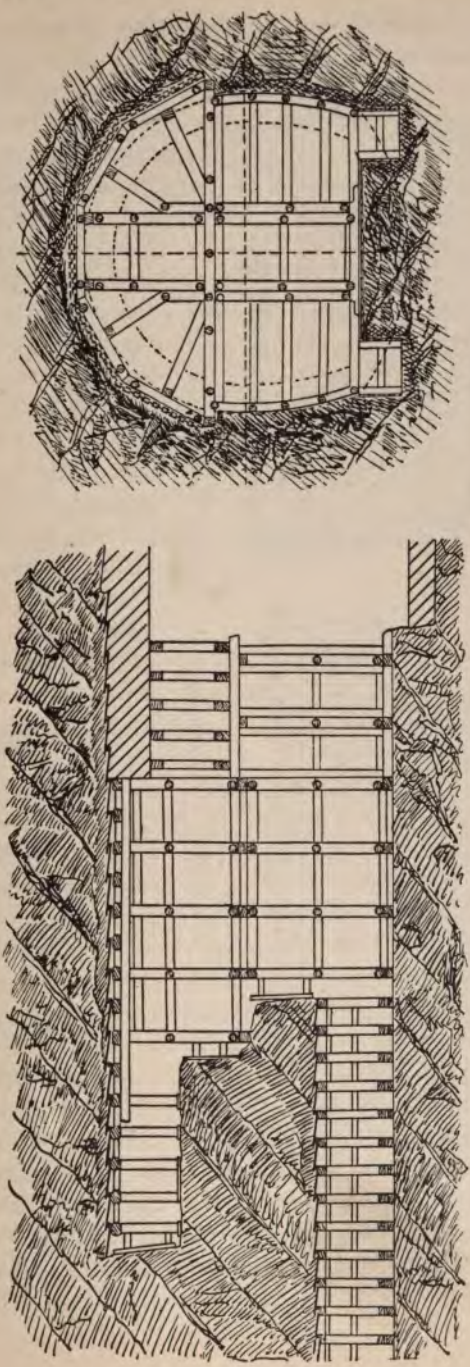


FIG. 163.—Method of excavating and timbering, Austrian system.

in Fig. 163. A modified method of timbering has been used more recently; it is illustrated in Fig. 164. It is known as the "New Austrian Method" and was first used in connection with the driving of the Aarlberg tunnel. In this last method, the crown bars are carried longitudinally and the poling boards transversely to the axis of the tunnel, whereas in the old method they were carried in a reversed order. The new method is best adapted in heavy ground, especially when loaded unsymmetrically. The centers for the masonry are carried closely to the full timbering, and thus, the excavation, timbering and lining are carried on simultaneously. The timbering, although abundant, is made up of short struts, easily knocked down or dismantled, which can be used over again.

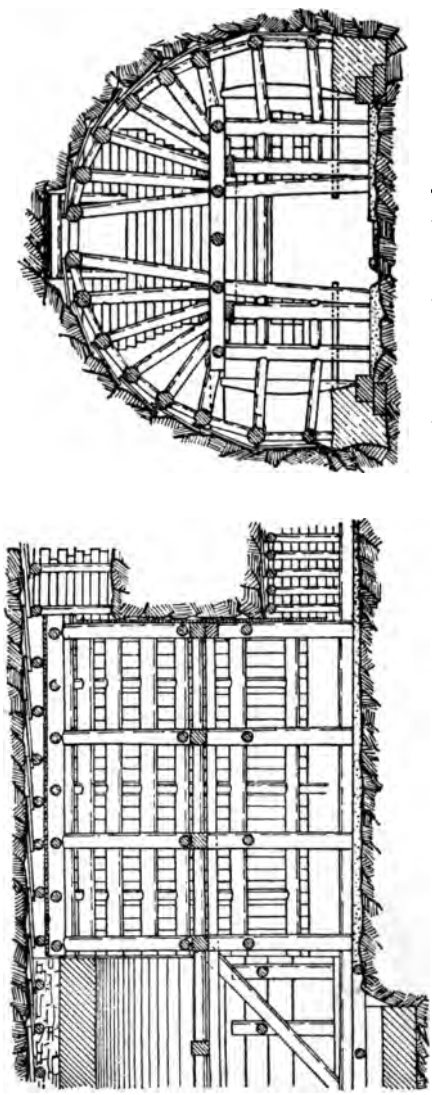


Fig. 164.—Method of excavating and timbering, New Austrian method.

Italian Method

This method is used only in very treacherous material, on account of its high cost. It has been used extensively in Italy, in connection with tunnels driven through the Apennine Mountains. The sequence of excavation is illustrated in Fig. 165.

A bottom heading is driven first, over a short distance and subsequently enlarged to the full width of the bore. Then part 3 is excavated, and the masonry invert and side walls are carried up to part 7. The top heading is then driven and widened to 5 and 6. Trenches are then excavated on each side of part 7, so as to enable the masonry to be carried up from the existing side walls up to the arch. Part 7 is then excavated.

It will be realized that the whole process of driving, timbering and lining is slow and costly, and warranted only in exceptional cases, where wages are low, as for instance in Italy.

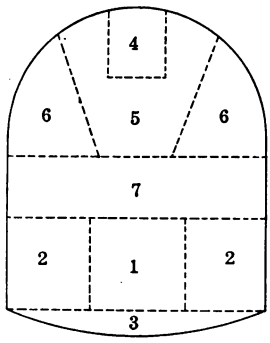


FIG. 165.—Sequence of excavation, Italian system.

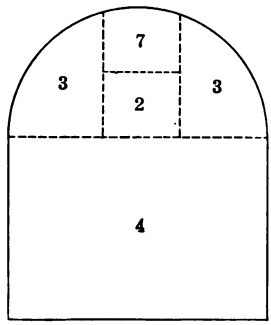


FIG. 166.—Sequence of excavation, American method.

American Method

The sequence of excavation is illustrated in Fig. 166. The method differs little from that used in connection with driving tunnel through rock or solid materials, except that a small heading is driven first for some distance, at the roof of the bore, being timbered usually with a three-piece set. Parts 3 and 4 are then gradually excavated and timbered in a manner similar to that illustrated in Fig. 45, radial struts supporting longitudinal crown bars, which, in turn carry transverse poling-boards. Longitudinal wall plates are then provided on each side of the arch, and a timber segmental arch is substituted to the temporary strutting, supporting the crown bars, as shown in Fig. 167. The bench is excavated usually with a steam or air-operated shovel. The method of timbering and lining is similar to that used in rock tunnels, described in Chapter V.

In driving a single-track, 900-ft. long tunnel, on the C.P.R. through loose and practically dry gravel, the following method was used, Fig. 168: In the arch of the bore, two side drifts 8 ft. high and 6 ft. wide were driven. A sill-piece 6 ft. long was first set to the elevation of the under side of the wall plate; on this were set up the posts and the cap, 4 ft. long, was cut to bevel to form a shoulder and prevent the posts from squeezing in.

With the drift frame in place, the face in front was walled with 1-in. breast boards, braced with inclined struts. All around the outside of the frame close lagging was entered and driven for-

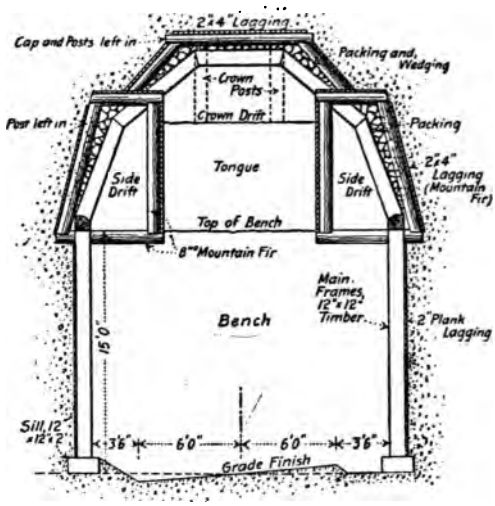


FIG. 168.—Method of excavating and timbering tunnel on the Canadian Pacific Ry.

ward by sledges. This lagging was made of 2 × 4 in. fir, in 5 ft. lengths.

After the side drifts had advanced about 20 ft., the top heading was driven in a similar manner, though this was only 4 ft. high, and the 8-ft. cap required a middle prop. The top heading connected the side drifts at the top; the top lagging of the side galleries was broken through, and the block arch of five 12 × 12-in. timber was set up on the wall plates, the latter being also 12 × 12-in. timbers. The arch sets were placed 15 in. center to center.

As the lower bench was excavated, the two sides were breast boarded with 2-in. plank, but the central part was allowed to

assume a slope. Round 6-in. timbers were placed horizontally, as the excavation proceeded, across the tunnel at the level of the wall plates and at 5-ft. intervals. Another tier of the same bracing was located 7 ft. lower down. Against these struts the lower boarding was braced.

In excavating the post-chambers the top breast board was removed and the gravel scraped away sufficiently to allow this board to be set forward 3 ft. A side-board was then inserted parallel to and just outside the wall plate to prevent side runs. In this manner, a chamber was cribbed down to grade at each side; and at grade, a 12 × 12-in. sill, 2 ft. long, was set. A post was then entered under the wall plate and resting on the sill, and the bottom of the post was pushed outward by a jack until the post was plumb.

While excavating the post-chambers, the unsupported wall plate formed a bridge, about 3 ft. long, from the gravel of the bench to the post already in; the drift-frames assisted in holding up these plates. When the ground would permit it, a space for two posts was excavated at one time.

Conclusions

In closing the review of the different methods of tunneling soft materials, let it be pointed out that those methods which enable a high rate of progress to be attained, thereby permitting the masonry lining to be built without delay, are to be preferred. The longer a bore driven through soft and unstable material remains unlined, the greater is the possibility for pressure to increase.

A method that is suitable in connection with driving through both soft and hard materials, with and without pressure, is to be preferred.

The possibility of building the masonry lining from the foundations up is to be given much weight, as underpinning is always an operation subjected to many contingencies.

The Belgian method can be used with advantage in soft materials not subjected to pressure, and poor in water-bearing strata, when the bore can be left without too much timbering for a short length of time, in short sections. If the roof of the bore is to be strutted, although in other sections of the bore pressure is not abnormal, the English and Austrian methods can

be substituted advantageously. These last-named methods become unfavorable and costly in heavy ground subjected to intense pressure and the new Austrian method can be used advantageously. The American method will be found advantageous in this country, especially in light materials not subjected to unsymmetrical pressure.

CHAPTER XV

PRESSURE ACTING ON TUNNELS DRIVEN THROUGH SOFT OR COHESIONLESS MATERIALS

The pressure to be sustained by the timbering and lining of tunnels driven through soft and more or less cohesionless materials such as sand, glacial deposits, gravel, clays, etc., is somewhat more definite than that resisted by tunnels driven

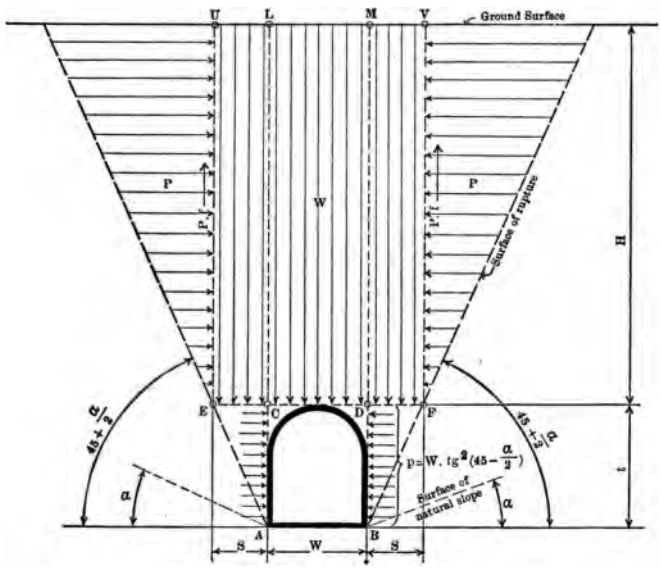


FIG. 169.—Diagram illustrating distribution of pressure on a tunnel driven through soft material.

through stratified or unstratified rocks possessing little cohesion or otherwise shattered or subjected to internal stresses due to squeezing or folding, etc.

Let Fig. 169 represent a bore driven through little overlaying material. If the latter was a liquid, like water for instance, the weight or vertical pressure W acting on a line C-D, passing through the arch of the bore, would be represented by C-D-L-M, and the weight per sq. ft. would then be $H.y$ where H is the over-

laying depth and y the weight of one cu. ft. of material, or of water in the present example. That is, the load acting on C-D would be a direct function of H.

As all materials more or less solid possess some cohesion, it becomes evident that the weight W becomes a function not only of H but also of the friction existing between the particles of the overlaying material.

If α is the angle of repose of the material penetrated, the value of which varies from a few degrees, as in quick-sand for instance, to 45° for naturally wet earth or for gravel, it is generally assumed that the angle between a horizontal line and the line of rupture is equal to $45° + \frac{\alpha}{2}$.

Through the mining and excavating process, the line C-D is usually lowered by a few inches in certain instances, and by a few feet in others, that is, the roof of the tunnel settles down according to the material penetrated and the skill displayed in mining. Thus, the surface between E-C and D-F receives a certain amount only of the reaction, due to the weight W, owing to the fact that the horizontal pressure exerted by the weights P, through friction f, counteracts the intensity or magnitude of W to an amount $2.P.f$.

Thus the intensity of W depends on H and on the cohesion of the material penetrated. The angle of repose α varies, being less for materials such as sand and being large for harder materials, or materials having more cohesion. The following table gives values of α for various materials together with their weight.

Material	Weight per cu. ft., lb.	Angle of repose, α, °
Sand, dry	98–103	30–35
Sand, naturally wet	113	40
Sand, saturated	128	25
Earth, dry	87	35–40
Earth, naturally wet	100	45
Earth, saturated	113	27
Clay, dry	100	40–50
Clay, wet	128	20–25
Sand and gravel, dry	113–115	35–40
Sand and gravel, wet	116	25
Gravel, polygonal	113	45
Gravel, rounded	113	30

A. Bierbaumer offers the following solution, serving the purpose to determine the intensity of the pressure or load W. Referring to Fig. 169 the following equations hold good:

$$t.p = t.y.H.\ tg^2\left(45 - \frac{\alpha}{2}\right) - 2.s.W\ tg\ \alpha \tag{1}$$

$$W = y.H - y.\frac{H^2}{w + 2s}.\ tg^2\left(45 - \frac{\alpha}{2}\right)\ tg\ \alpha \tag{2}$$

$$p = W.tg^2\left(45 - \frac{\alpha}{2}\right) \tag{3}$$

The unknown values W, p and s are to be found. All values are for 1 lineal ft. of tunnel, y being the weight of 1 cu. ft. of the material overlaying the bore. The meaning of the other figures are given in Fig. 169.

By substituting eq. 3 in eq. 1 we have:

$$W.t.tg^2\left(45 - \frac{\alpha}{2}\right) = y.H.t.tg^2\left(45 - \frac{\alpha}{2}\right) - 2.s.W.tg\ \alpha$$

Now if we make $g^2 = tg^2\left(45 - \frac{\alpha}{2}\right)$, by substituting further equation 2 in 1, we have:

$$\left(y.H - y.\frac{H^2}{w + 2s}.\ g^2.tg\ \alpha\right)g^2.t$$
$$= y.H.t.g^2 - 2s\left(y.H\text{-}y.\frac{H^2}{w + 2s}.g^2.tg\ \alpha\right)tg\ \alpha$$

by resolving and reducing we have

$$s^2 = 2.\frac{H.g^2tg\alpha - w}{4}.s - \frac{H.t}{4}.g^4 = 0$$

if now we make $z = g^2.tg\ \alpha$ then

$$s = \frac{z.H - w}{4} \pm \sqrt{\left(\frac{z.H - w}{4}\right)^2 + \frac{H.t}{4}\ g^4} \tag{4}$$

Only the positive value of the root can be used, and in order to determine W, this value is substituted in equation 2. Then:

$$w + 2s = \frac{z.H + w}{2} + \sqrt{\left(\frac{z.H - w}{2}\right)^2 + H.t.g^4}$$

and

$$W = y.H\left(1 - \frac{z.H}{\frac{z.H + w}{2} + \sqrt{\left(\frac{z.H - w}{2}\right)^2 + H.t.g^4}}\right) \tag{5}$$

by calling C the expression within the parentheses we have $W = C.y.H$ where C is the reduction coefficient, and is always less than 1.

The value of g^4 for:

α =	15	20	25	30	35	40	45	degrees
is	0.35	0.24	0.17	0.11	0.07	0.05	0.03	

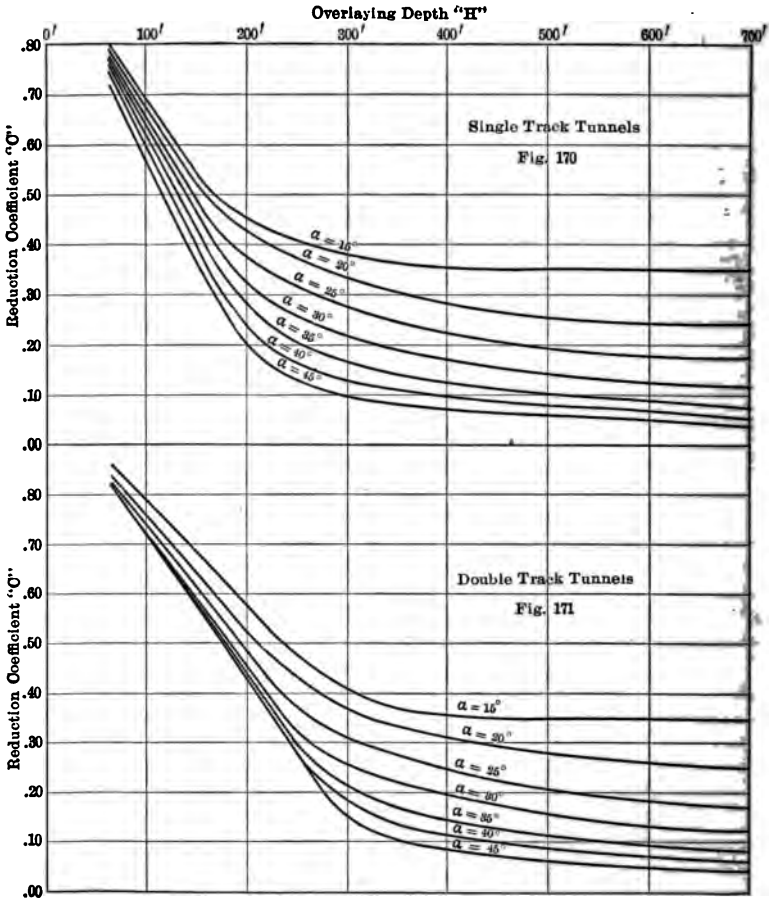
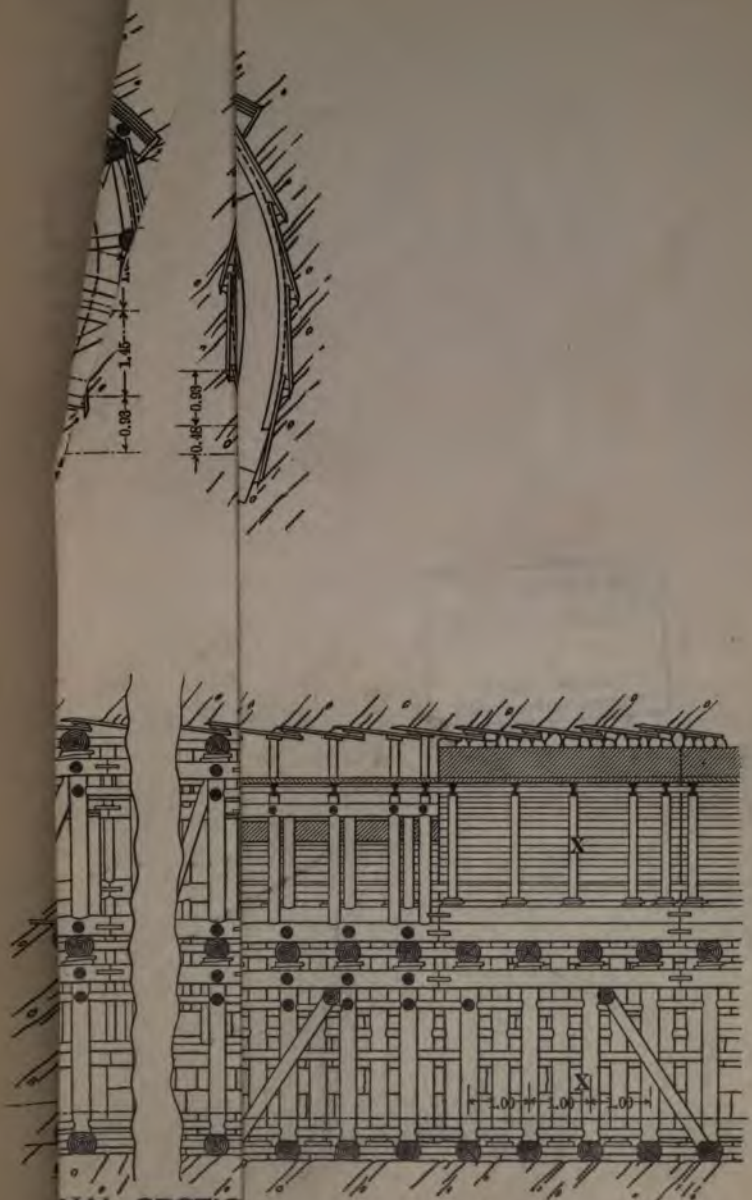


FIG. 170.—Curves giving the value of the reduction coefficient "C" to be used in the formula $W = C.y.H$ (single track tunnels).

FIG. 171.—Curves giving the value of the reduction coefficient "C" to be used in the formula $W = C.y.H$ (double track tunnels).

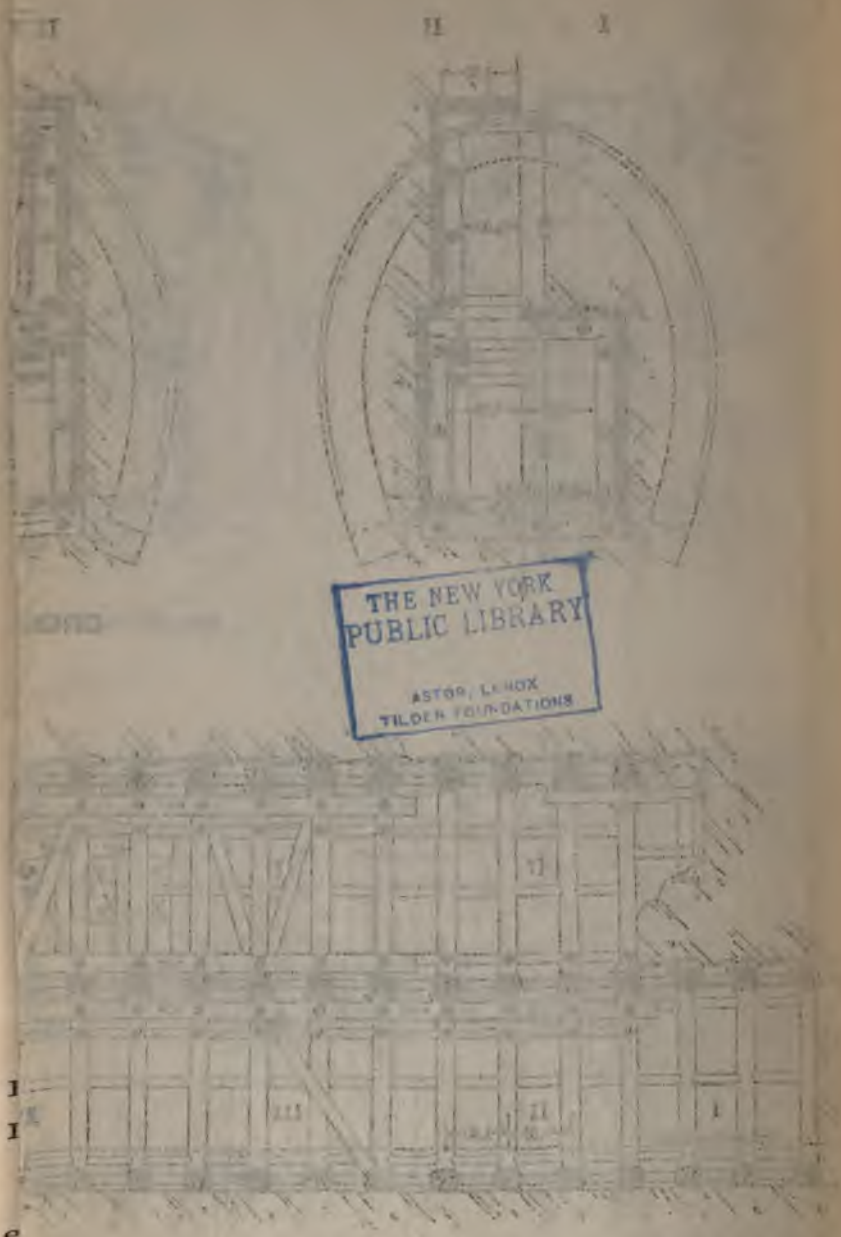
The value of the reduction coefficient C as obtained from equation 5 gives results somewhat low for practical purposes, and Bierbaumer gives a table of more conservative values of



NAL SECTIO

and timbering, F

(*Facing page* 178.)



THE NEW YORK
PUBLIC LIBRARY
ASTOR, LENOX
TILDEN FOUNDATIONS

C for single- and double-track tunnels, which have been plotted as shown in Figs. 170 and 171 respectively.

In the Ratkonyer single-track tunnel, with an overlaying depth of about 147 ft., Engineer Gröger found that, in dry materials, the pressure at the roof of the bore was about 7300 lb. per sq. ft.; α was found equal to 35° and y was 112 lb. per cu. ft.

Then in Fig. 170, $C = 0.45$ and $W = 0.45 \times 112 \times 147 =$ 7400 lb. which value checks fairly well with the value observed.

The above theory will be found of material assistance in determining the pressure to be expected in tunnels driven through soft or more or less cohesionless materials, yet judgment must be exercised in applying it in practical cases as it might become a dangerous tool in inexperienced hands.

The Bruggwald Tunnel

This single-track bore, driven in Switzerland in 1907–1908, is 5670 ft. long. The maximum depth about 2000 ft. from the north portal is 230 ft. The materials penetrated were a grayish marl, soft in places and hard in others. On the north side some glacial deposits, sand and peat were penetrated. Owing to the small overlaying depth, daily rainfalls were perceptible in the tunnel.

The bore was driven on a 12°/00 grade, 3870 ft. being driven from the south portal and 1800 ft. from the north portal.

The shale, when exposed to air and water, swelled rapidly and it was necessary to drive the heading heavily timbered and even sheeted in places. The sequence of excavation is illustrated in Fig. 172. A bottom heading I, about 10 ft. wide and 11 ft. high, was driven first over a distance of 10 to 15 ft. and immediately timbered. A top heading II, about 9 ft. wide, was then driven and timbered heavily and sheeted as shown in III. It was then enlarged on one side, IV, and then on the other, V. The following cycles of excavation, timbering and lining are fully illustrated by VI to X.

In certain sections the ground was very heavy, the floor raising in several instances, thus necessitating heavy timbering. Near the north portal, where the overlaying depth was only about 50 ft., a serious cave-in occurred clear to the ground surface. Twelve men were buried, seven of them being killed. One of the men saved was buried for 11 days, being rescued through a heavily timbered drift about 40 ft. long.

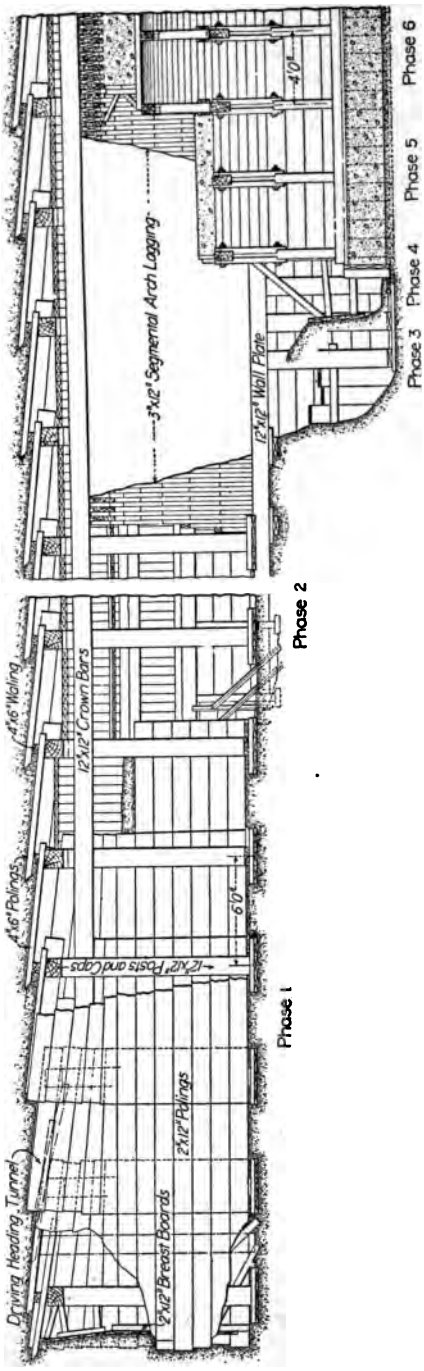


FIG. 173.—Longitudinal section showing method of excavation. Siphon under Lake Washington canal, Seattle.

The bore was lined with masonry throughout, carried on steel I-beam centers. In general the timber sets were spaced from 4 to 5 ft. center to center. No timbers save poling boards, were left back of the lining. A masonry invert was necessitated over a length of 1935 ft.

Driving of the bore was done by hand, except in hard material where augers were used.

Construction Methods of Siphon under Lake Washington Canal

This siphon being part of a trunk sewer system at Seattle, has a length of 400 ft. It was driven chiefly through clay. The details and sequence of excavation and construction are illustrated in Figs. 173 and 174.

First, a heading, heavily timbered with 12 × 12-in. struts and caps was driven, 4 × 6 in. poling boards being used. Owing to their length, the caps were supported with a 12 × 12-in. post in the center. The sides of the heading were sheeted with 2 × 12-in.

boards. The crown bars were 12 × 12-in. material. The face of the bench was heavily sheeted and braced against the concrete lining.

Two tracks were laid in the tunnel, extending clear to the face of the bench. The material from the heading was conveyed and dumped into cars on the tunnel grade in wheelbarrows.

First the invert concrete was laid throughout the width of the bore. To lay the masonry in the side walls, a timber platform carrying a track was provided, high enough to enable cars to pass underneath, holding the forms for the side walls. The arch concrete was carried on wooden centers about 4 ft. center to center, supporting the lagging.

The roof of that part of the bore fully excavated was supported by 3 × 12-in. segmental arch lagging which was left within the concrete

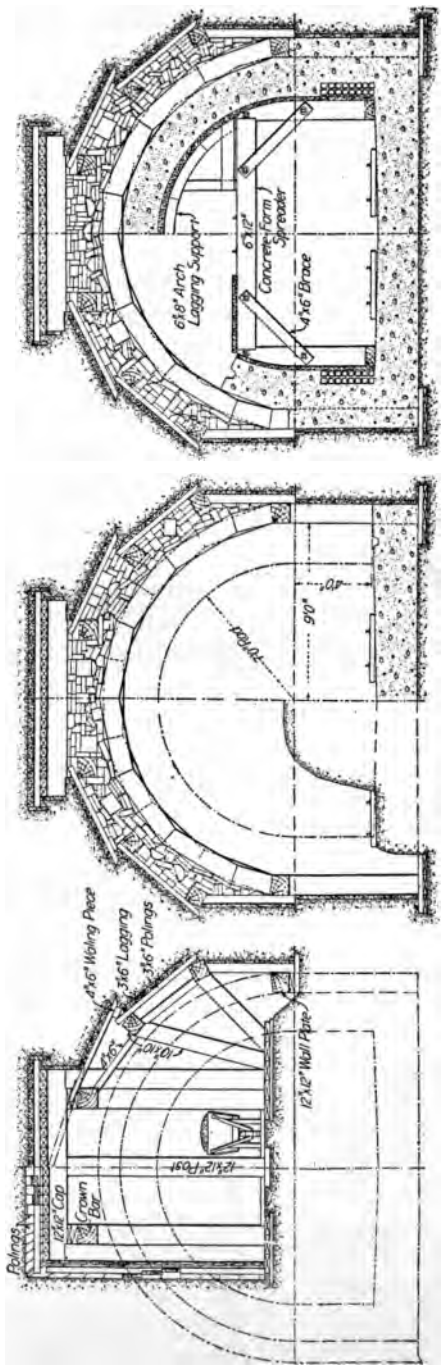


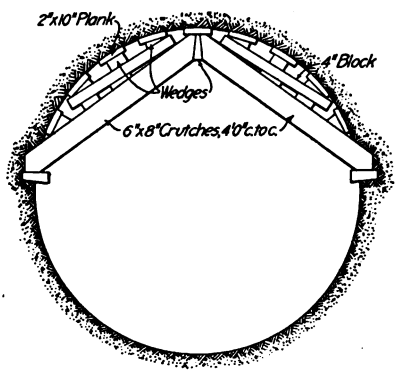
FIG. 174.—Cross sections showing method of excavating, timbering and lining. Siphon under Lake Washington canal, Seattle.

lining. The concrete for same was mixed in the proportion 1:3:5.

From the accompanying figures, it will be realized that a large amount of timber and packing was left within the lining and that the excavation was large.

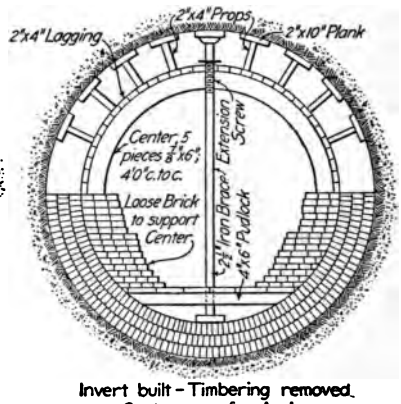
Brick Sewer built in the Sanitary District of Chicago

The bore for this sewer is 1050 ft. long and was driven through stiff blue clay. In places there was only 12 ft. of covering over the roof of the tunnel. The work was carried on by two night shifts of miners and muckers and a day shift of bricklayers,



Mining complete and Timbering in Place to support Roof

FIG. 175.



Invert built - Timbering removed. Centers set for Arch

FIG. 176.

FIGS. 175 and 176.—Method of timbering and lining brick sewer built in the sanitary district of Chicago.

working 8 hr. each. Fig. 175 shows the method of timbering in good stiff clay. In poor ground the crutches were made longer with the lower end set below the spring line, and the 2 × 10 in. planks at the roof were placed closer together. The excavated material was dumped from the shaft which had been sunk to attack the headings, into cars and hauled 3 miles away. Fig. 176 shows the method of setting up the centers for the arch after the invert is built and timbering removed. In each heading the average progress for 24 hr. was 12.5 ft. The average number of brick laid per 8 hr. per bricklayer was 3000. The cost of the sewer was as follows:

Items	Cost per lin. ft.	Cost per cu. yd.
Excavation	$6.49	$2.43
Waste disposal	2.05	0.77
Lumber	0.40	
Power	0.15	.....
Miscellaneous	1.26	.....
Brick masonry	9.35	.....
Labor	.....	4.40
Brick	.....	4.09
Cement	.....	0.57
Sand	.....	0.29
Total	$19.70	$9.35

Method of Constructing a Sewer in Brooklyn

The sewer was 13.5 ft. clear diameter, lined with 16 in. of brickwork, with a granite block invert. The tunnel was driven

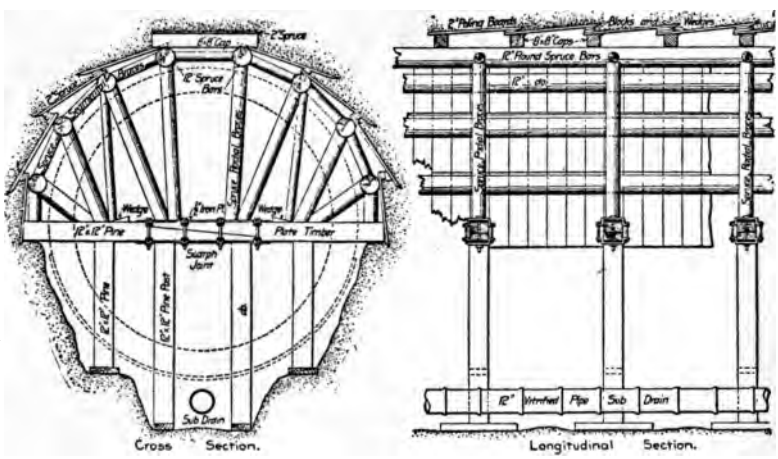


FIG. 177.—Method of excavating and timbering a sewer in Brooklyn, N. Y.

through fine sand carrying much water. This sand would not stand up during excavation, but was hardly unstable to be classed as quicksand. The work was carried on from two shafts.

In excavating this tunnel, Fig. 177, a drift 6 ft. wide and 7 ft. high was first driven at the bottom center of the section. The

primary purpose of this drift was to drain the sand and to facilitate this, a tile sub-drain was laid about 2 ft. below the bottom of the invert and left in place. Almost simultaneously with the bottom drift, another drift was driven at the top of the section, 8 ft. wide and 7 ft. high and both drifts were kept about 50 ft. ahead of the full section work. As they were driven, these drifts were held by the usual frame and poling boards with the face bulkheaded and held up by struts or rakers. The section was enlarged from the heading by excavating on each side, inserting the roof-bars, radial struts and poling-boards one after the other. The radial struts were removed as the lining was built, but all other timbering was left in place, with all the interstices filled with concrete.

CHAPTER XVI

SIPHON TUNNELS

Siphon tunnels are driven for the purpose of crossing under an area covered by a body of water such as a lake or river, as the Colorado River siphon for instance, driven under the Colorado River, or the Hudson River siphon, or the Croton Lake siphon, or else under a depression or valley such as the Moodna, Walkill and Rondout siphons, driven in connection with the Catskill Aqueduct.

Siphon tunnels are driven with or without the assistance of compressed air, according to the depth overlaying the bore and also the material penetrated.

As compressed air is used for the purpose of counteracting or counterbalancing the external hydrostatic pressure acting upon the tunnel lining, its use is limited in connection with bores driven at a relatively small depth, for the very reason that human beings cannot work efficiently under air pressure much over 40 lb. per sq. in., although in certain instances, men have worked under higher pressure for a short duration of time.

When the topography of the site selected for the location of a siphon tunnel necessitates it to be driven at great depth below the surface, in which case compressed air could not be of assistance, it is of absolute necessity that the material penetrated be perfectly impervious.

A notable example of siphon driven at great depth is the Hudson siphon, located some 1100 ft. below the Hudson River surface, also the Rondout siphon driven at an average depth of about 500 ft. below the ground surface.

Location of Siphon

The location of a siphon under a body of water, or penetrating water-bearing strata, is a very complex problem, the successful solution of which requires the cooperative work of the geologist and engineer.

In selecting a location, the steps usually followed consist in

making a thorough geological survey, using such existing data as are available, if any, and completing these by borings made in the proposed axis of the tunnel. Wash and core borings are then made according to the material penetrated, and often porosity tests are made also.

Probably the most noteworthy example of geological surveys and tests made in connection with tunnel work are those carried on in connection with the siphon or pressure tunnels of the Catskill aqueduct, and there is no question but that the results gained thereby have fully warranted the cost of making these. Upon the data collected from the surveys and tests, depend, 1. the final location of the bore; 2. the shape of its cross section; 3. the strength of the lining; 4. and last but not least, the driving method best adaptable.

In soft and pervious materials such as quicksand, sand, gravel, alluvial or glacial deposits, the bore is given a circular section and it is driven at a relatively shallow depth under compressed air, with or without a shield.

In hard but pervious materials, the bore is driven also at a relatively shallow depth under compressed air, but without a shield.

In hard and impervious material, the bore is driven at great depth, sometimes without shield or compressed air.

The approach of siphon tunnels can be made very steep, a vertical shaft sunk usually for this purpose.

The Colorado River Siphon[1]

It is part of the Yuma irrigation project and is located at the town of Yuma, about 350 ft. downstream from the Southern Pacific Ry. bridge. Nine borings were made along the route selected, as shown on the profile, Fig. 178, and in each of them soft sandstone or indurated sand was encountered. Judged by the particles brought up in the wash borings, the sandstone is of the same general character as the bluff which flanks the eastern border of the river at this point. The borings showed this hard formation to dip toward the west, being about 50 ft. below the low-water bed in midstream and some 80 ft. under the surface on the site of the California shaft. Overlaying the sandstone there is at low-water stage, at least 25 ft. of very fine silt which acts as a partially impervious blanket to the material below.

[1] Condensed from a paper by Francis L. Sellew.

It was assumed on account of this heavy blanket of overlying silt, that a tunnel, well inclosed in the sandstone, would encounter comparatively little water and might be driven without the aid of compressed air. To accomplish such an object, it would be necessary to sink shafts well into the lower and harder stratum, seal them against the water from above, and then cut through the shaft on line of the tunnel.

The profile first selected for the tunnel is shown in Fig. 178 by dotted lines. It was so situated that at no point did the tunnel approach nearer than 20 ft. to the surface of the sandstone, the shafts on either side being 130 ft. in depth. When it

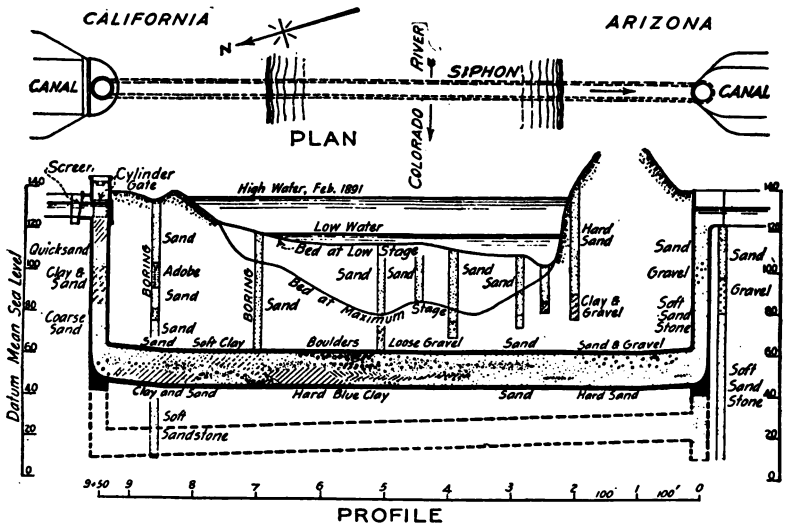


FIG. 178.—Plan and profile of Colorado River siphon at Yuma, Arizona.

became necessary to use compressed air the elevation of the tunnel was raised to reduce the working pressures. The full lines show the work as built.

The tunnel is designed to pass 1400 sec. ft. with a loss of head of 2 ft. After considerable study of various formulæ, a circular section 14 ft. in diameter was selected, the thickness of the shell being 24 in.

Design of Shafts.—Before deciding on this feature, a careful examination was made of various shafts and bridge piers which had been successfully constructed by the open-caisson method. Some characteristics are given in the table below.

TABLE GIVING DETAILS OF SOME CONCRETE CAISSONS SUNK BY THE OPEN METHOD

Location	Depth, ft.	Diameter, ft.	Material penetrated	Kind of caisson	Skin friction per sq. ft.	Progress of sinking
Wilkes-Barre, Pa., coal mine shaft.	80	59.5 ×28	Sand, gravel, quicksand.	Reinf. concrete.	.....	1.5 ft. in 10 hr.
Ft. William, Ont., bridge piers.	60	31	Water, sand, gravel, clay.	Concrete, st. shell.	275 to 300 lb.	5 months.
Red River, La., bridge piers.	90	37	Water, sand, gravel, clay.	Timber lined, w. concrete.	Sunk by own weight	4 ft. in 10 hr.
Glasgow, tunnel shaft.	75	76	Sand, clay....	Double C. I. shell w. concr.	.....	8 ft. per month.
Blackwall tunnel, London.	77	48	Clay, sand....	Double steel cyl. w. concr.	560 lb. at bot.	1 ft. in 24 hr.
Siphon de Clichy, Paris.	77	10	Sand, gravel, marl.	C. I. segments..	.....	10 ft. per month.
Greenwich tunnel, London.[1]	65	35	Clay, sand.....	Double steel cyl. w. concr.	.....	.....

These structures vary in diameter from 10 to 75 ft. and in depth from 65 to 100 ft. The piers of the Poughkeepsie bridge were also sunk by this process to a depth of 120 ft. or more. The method consists in building the caisson as an annular ring, generally circular, but often octagonal, with walls sufficiently thick to resist the pressure encountered. When the shaft is on shore, a pit to meet the outside dimensions of the caisson is first dug to a depth of 12 or 15 ft. In the bottom of this pit the cutting-edge is assembled and upon it the caisson is built to a few feet above the ground surface. Excavation inside the caisson is then conducted in such a manner that the surface gradually sinks into position and its walls are built up from time to time as their tops approach the surface of the ground. The shafts and piers shown in the table above have been constructed in this way, generally with little difficulty. It appears from the seven structures listed that concrete has played an important part in all of them except at the siphon de Clichy, where cast iron was used. Excluding the Wilkes-Barre shaft, which is built of reinforced concrete, the masonry has in all cases been protected by metal or timber attached to the cutting-edge, the masonry being used as a filling between these protective skins. There appears no good reason, however, why these protective skins

[1] 24 ft. open; remainder in compressed air.

could not have been omitted in nearly all cases, especially where the structure was surrounded with earth.

H. L. Wiley, who had charge of the piers sunk at Fort William, Ont., says: In many cases an all-concrete caisson could be used to great advantage. The cutting-edge of the caisson could be protected and strengthened with a sheathing of steel plate for 5 or 6 ft. A channel riveted to the inside lower edge would hold the first section in shape and offer support for the concrete forms at the cutting-edge. This channel would be subject to the heaviest duty, and with the plate would prevent serious damage if boulders or timber should be encountered. The steel shell of an open caisson is often of no actual value except as a form for the concrete, and in cases where it might easily be eliminated it would seem to be an unnecessary expense.

Experience with the other caissons described indicated that a concrete structure with no reinforcement except at the cutting-edge and some few rods at the junction of successive days' work would answer all requirements, especially for such locations as Yuma, where silt and sand with practically no obstruction were anticipated, and so the shafts of the Colorado siphon are of this type.

Size of Shaft.—Under ordinary conditions the diameter of the shafts should be the same as that of the tunnel, in this case 14 ft. The uncertain conditions made it necessary to provide for all contingencies, and there was a possible chance that a shield might have to be introduced. The Arizona shaft, from which it was proposed to drive most of the tunnel, was given a finished diameter of 20 ft. and the California shaft 14 ft.

Thickness of Shaft Walls.—An examination of the details of the various caissons listed shows that the concrete walls have in general had a thickness of about 5 ft. This thickness has demonstrated its ability to resist the strain due to sinking and give a practically water-tight structure when in place. The caisson should, if possible, have sufficient weight to overcome the skin friction encountered in sinking, as the expense and annoyance of adding weight for this purpose will be eliminated. The amount of this skin friction varies widely with different materials: At Fort William it was from 275 to 300 lb. per sq. ft.; at the Blackwall tunnel 560 lb. per sq. ft.; in the design of piers for the Manhattan bridge it was assumed in sand as 500 lb. per sq. ft. At the piers on the Red River in Louisiana its intensity is not given,

but the statement is made that the caisson with walls of concrete 5 ft. thick sank of its own weight. Mr. Wiley, in his article on the Fort William bridge piers, says: "A wall thickness of 5 or 6 ft. gives weight enough to overcome any friction which may develop ordinarily."

Provision was made to give the shafts a wall thickness of 5 ft., so there would be approximately 5 cu. ft. of concrete opposed to each square foot of outer skin, and assuming the weight of masonry at 140 lb. we would have 700 lb. of caisson for each square foot of skin. This would overcome any of the frictions given above. It was believed, however, upon considering the materials through which the structure would pass, that this provision was excessive, and at a point 10 ft. above the cutting-edge an offset of 18 in. was made in the inside skin, reducing the wall thickness to 3.5 ft., as shown in Fig. 179. This increased the diameter of the Arizona shaft to 23 ft., and the diameter of the California shaft to 17 ft. This offset would provide a favorable support for an air-deck in case it became necessary to resort to the pneumatic process for sinking, and if additional weight was required it could readily be placed upon this shelf.

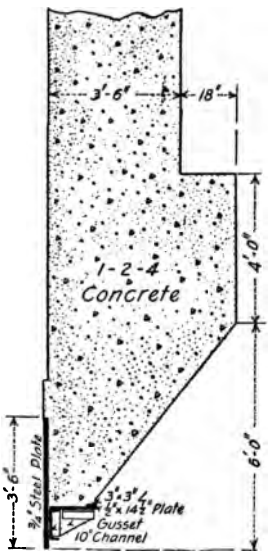


FIG. 179.—Section at cutting-edge, Arizona shaft of Yuma siphon.

Sinking the Arizona Shaft. — The ground in the vicinity of the shaft was leveled to an elevation of 147 ft. above sea level, and a pit meeting the outside dimension of the shaft was excavated to a depth of 10 ft. In the bottom of the pit the cutting-edge, Fig. 179, was assembled. The bottom 10 ft. was constructed with wooden forms, but above this point steel forms were used. These were arranged to inclose an annular ring of the dimensions of the caisson walls, the total height of the forms being about 4 ft. When the concrete had hardened sufficiently the forms were slacked and raised to their next position with a derrick.

The material encountered down to El. 120 was a perfectly dry, hard sand. At this point water was encountered in small quan-

tities continually increasing as the work went on. At first, ordinary sinking pumps, with capacities ranging from 150 to 300 gal. per min., were installed, but as the volume increased it was clear that the delays incident to pump repairs necessitated by the continual clogging from the sand and the eating out of the packings by the same agent would soon be a serious matter. Finally there was installed a vertical 6-in. Byron Jackson 2-stage centrifugal pump, belt connected to a 65-H.P. gas engine. This pumping-unit handled at times 1200 gal. per min. against a head of 100 ft.

Excavation still continued by pick and shovel, and the cutting-edge on March 9 had arrived at El. 74. At this point, when the water was pumped down sufficiently for excavation to continue, the cutting-edge was under a hydrostatic pressure of about 46 ft. and repeated blows under the cutting-edge occurred, driving the men from the work. It was thus apparent that the limit of operations under such conditions had been reached, so it was decided to allow the caisson to be flooded and to dredge the material. A derrick was then provided to handle a ½-yd. clamshell bucket, and the operation of this new equipment began. The material to be dredged was quite hard, and it was necessary to attach steel teeth to the bucket in order to penetrate it. On March 16, the cutting-edge reached El. 69 and the excavation had been carried to a point 10 ft. below, but the caisson failed to penetrate. The centrifugal pump was put to work and water was lowered a few feet. The caisson immediately began to settle, a penetration of 3 ft. being accomplished in 1-¼ hr. When the cutting-edge was about El. 66 and the core was several feet below the cutting-edge, no penetration occurred. The pumps were started and the water inside lowered to a point about 15 ft. above the bottom of the caisson. A blow occurred, followed by an immediate penetration of about 6 in. This blow resulted in some disturbance of the surface immediately outside the caisson. The cutting-edge had then reached El. 65 and the excavation was 10 ft. below this point. Lowering the water by pumps gave no penetration. On March 23, the water inside was 7 to 8 ft. above the cutting-edge. No blow occurred and penetration was accomplished. Later on the same day, with the water 23 ft. above the cutting-edge, a blow occurred. On March 28, the cutting-edge reached El. 58. Lowering the water inside a reasonable amount failed to produce any movement of the caisson and it was deemed inadvisable

to lower the water further because of the blows which usually followed.

Pipes were jetted down on the outside of the caisson to about 5 ft. below the cutting-edge. The excavation on the inside was carried about 10 ft. below the cutting-edge and dynamite was exploded in the outer holes to break up the annular ring which was preventing the movement. This method of operation was carried on until the cutting-edge had reached El. 55.5. It was then decided to use divers for excavating, which was made by a clamshell bucket to a point 8 or 10 ft. below the cutting-edge. The pump was then used to lower the water to about 50 ft. above the cutting-edge. A diving stage was suspended above water level and a diver bored holes 5 ft. below the cutting-edge, loading and exploding these with dynamite. Yet the caisson refused to move and the skin friction was about 400 lb. per sq. ft. Water jets were introduced around the skin to relieve the friction. This helped materially, and finally the cutting-edge reached 10 ft. below the grade selected for the tunnel and sinking was then suspended. The caisson was loaded with a total weight of 2500 tons when landed.

Sinking the California Shaft.—The method followed in sinking this shaft was substantially the same as that used in connection with the Arizona shaft. At times the divers operated under 110 ft. of water. Sinking the caisson required 320 tons of steel rails and cement.

Work under Compressed Air.—It was decided that the most feasible method of sealing the shafts to the sandstone would be by the pneumatic process. It was considered that once the seal was accomplished it might be possible to drive the tunnel in normal air, but on account of the uncertainty of this it was believed best to install a sufficient pneumatic plant to drive the entire tunnel by this method if the conditions required.

The equipment consisted of three compressors, a vertical lock and miscellaneous accessories. The compressors had a combined capacity of 4000 cu. ft. of free air per min. compressed to 40 lb. pressure.

An air-deck of timber 24 in. thick was constructed in the shaft at El. 83.1. The vertical lock was set up at the surface and 4-ft. tubing extended from the lock through the air-deck. The shaft being previously filled with sand to El. 42, a concrete plug 5 ft. thick heavily reinforced with steel was placed with its top at El.

47. The tunnel was then driven for 50 ft. from the Arizona shaft, the end bulkheaded, and the air taken off. In this 50 ft. of completed tunnel the horizontal lock, which was 6 ft. in diameter and 22 ft. in length, was installed. Cages were put in the shaft and driving of the tunnel under compressed air was started.

By this time it was apparent that it would be necessary to carry pressure for the entire length of the tunnel, and preparations were made to that end.

The difference in pressure for the upper half and for the lower half of the tunnel made it advisable to drive the upper portion first. The general program was to drive about 10 ft. of the upper half which was supported by segmental plates of No. 11 steel. The plates were 1 by 3 ft. Around the edges of these plates 2-in. angles were riveted, through which were punched holes for ¾-in. bolts. These holes were accurately spaced a uniform distance apart, so that it was possible to break joints every ring of plates. While the excavation was being made the plates were held in position by trench braces resting on the bench. The main use of the plates was to prevent the escape of air. After 10 or 12 ft. of the upper portion of the drift had been driven, concrete ribs with wooden lagging were put in position and the masonry placed. By this method 50 or 60 ft. of arch was completed. The pressure was then raised to meet the conditions of the invert and the bottom half of the tunnel constructed in 10-ft. lengths.

In general, about 21 ft. of the top of the arch was protected by plates, and only in rare instances was it necessary to extend the plates to the spring line. In a few places temporary supports were required on the invert for a short distance below the springing line, but in the main no invert supports were necessary. After a length of invert had been completed to within about 2 ft. of the arch, a bulkhead made of sandbag was built at the end to prevent water from coming in on the work while the arch was being driven under lower pressure.

On June 4, the California shaft was unwatered and the work of cutting through the walls of this shaft from the tunnel was carried on under normal air. The air pressure has in general been between 27 and 32 lb. per sq. in. above atmospheric. While there were a few cases of caisson disease, serious ones were extremely rare. There was one fatality. The siphon was put in service during the month of June, 1912.

The Hudson River Siphon

Various projects have been elaborated for the crossing of the Catskill aqueduct over or under the Hudson river. After taking into consideration different projects of bridging the river, or of laying steel pipes on the river bottom, an inverted siphon tunnel was decided upon. Its final location was selected after 226 preliminary borings had been made on fourteen different cross sections of the river. The final location is known as the Storm King Crossing, Fig. 180.

Both wash and core borings were made, but, in general, wash borings gave unsatisfactory results, as the bottom of the river

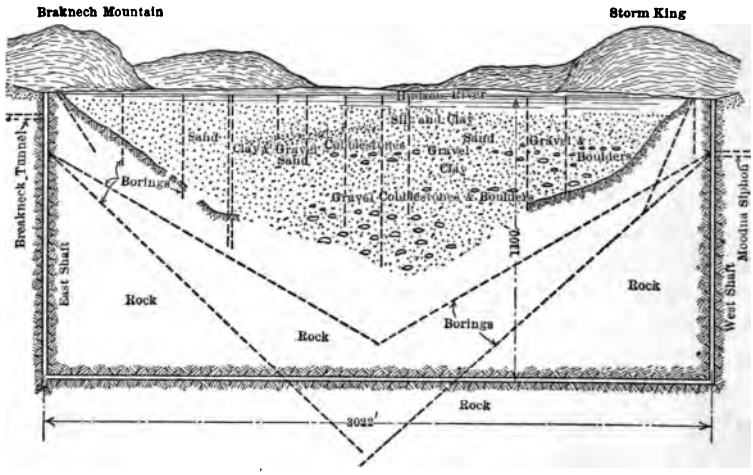


FIG. 180.—Hudson siphon.

was formed of glacial drifts, sand and gravel with boulders, together with fine silt.

Briefly enumerated, the following test borings were made in order to ascertain the proper depth of the tunnel below the surface. The exploratory work was carried on both on the river banks and in the river. Borings were made in the river by means of wash and core drills operated from scows. This method was costly, tedious and slow, on account of navigation which could not be interrupted and also on account of the tides. Several years were spent in accomplishing this work, both vertical and inclined core borings being made.

Vertical borings made across the river gave only partial results

and indefinite information as to the exact location of bedrock, and there was no indication showing that the rock penetrated was absolutely impervious and free from seams; therefore inclined borings were made subsequently from chambers blasted out of the rock, in two shafts, each located on the river banks.

Two sloping holes, 1830 and 2050 ft. long, were driven from the east and west banks respectively at an angle of 40 to 45° with the horizontal, and they intersected each other very nearly as shown in Fig. 180 and reached a depth of about 1560 ft. below the surface.

Two more holes about 1650 ft. long were then driven at an angle of 23 to 26° with the horizontal, intersecting each other, their bottom being at about El. 960 ft. below the surface. From the information thus obtained it was decided to locate the bore at El. 1100 ft. with about 200 ft. of overlaying rock. The material penetrated was chiefly massive and gneissoid granite, free from serious faults or crushed zones.

Two shafts were then driven to the 1100-ft. level and timbered, and the headings of the horizontal tunnel were started. In general little water was encountered, except on one occasion, in the tunnel, but the shafts were fairly dry.

The Tunnel.—It is 3022 ft. long and driven on a 0.1 per cent. grade. Fig. 180 illustrates the cross section and lining of the tunnel. Both the shafts and tunnel were 14-ft. inside diameter. Although the tunnel was circular in cross section, the bore was driven with a flat bottom or floor 10 ft. wide, thus enabling tracks to be laid thereupon conveniently.

Very elaborate compressor and pumping plants were provided on each side of the river, and driving proceeded speedily without unusual difficulties. A concrete bulkhead was built 200 ft. from the east shaft as a protection against flooding, and an adequate pumping plant was installed between the bulkhead and the shaft. A water-bearing seam was struck about 270 ft. from the east shaft but it was successfully sealed with concrete.

Driving Method

The top heading and bench method was used on both sides of the bore. Usually four drills mounted on columns were used in the heading and two on the bench mounted on tripods.

In the west shaft the average progress was about 270 ft. per

month. Where the ground was bad, a roof made of structural steel shapes was provided, as some shelling of the rock took place and delayed the driving progress.

At the east heading a horizontal diamond drill hole, about 500 ft. long, was driven in the face of the heading so as to ascertain the material penetrated ahead. The rock proved to be solid in general and practically free from water-bearing strata.

Concreting and Grouting

Concrete was delivered to the tunnel through the west shaft where a concrete plant had been installed. Concrete was delivered to a twin hopper car on the shaft cage, hence in smaller cars running on the tunnel grade and hauled to the forms by electric trolley locomotives. Steel forms were used, the invert being laid first, then the lower half of the lining and finally the upper half.

As hydrostatic pressure was high, corresponding nearly to the full head of overlying water, a special grouting method had to be used. Grouting under low pressure was first accomplished, using a Caniff grouting machine. The high-pressure grouting was made by pumping water with a Cameron pump into the grout tank, thus raising the pressure as high as 600 lb. per sq. in. This method was very successful in general, only a few cracks being made in the lining, and these were repaired without much trouble.

Croton Lake Pressure Tunnel or Siphon

It is located on the line of the Catskill aqueduct, about 300 ft. below water level of Croton Lake, and consists of downtake and uptake shafts 309 and 305 ft. deep respectively, and of a tunnel 2639 ft. long.

Explorations and Data as to Geology[1]

Six drill holes have been made on this proposed Croton Lake crossing, one on either side just at the margin and four others within the intermediate space of 1400 ft. These inner four have been made from rafts floated on the lake and have penetrated water, drift cover and rock, as shown in Fig. 181. The

[1] Condensed from "Geology of the New York City Aqueduct," by Charles P. Berkey.

depth of the pre-glacial Croton valley is pretty accurately determined at 0 ft. or sea level. There is no reason to expect a gorge or inner channel of any consequence. The drills have penetrated only one formation, *i.e.*, Manhattan schist. These test holes are believed to be near enough together to eliminate the possibility of any formation appearing at tunnel grade.

Rock Condition.—The two varieties of schist, (1) the coarse garnetiferous quartz-mica rock, which is a metamorphosed former sediment and (2) the darker, close-grained hornblendic rock that is believed to represent an igneous intrusion, both occur in the cores brought up by the drills. Holes Nos. 3 and 4, Fig. 181, at the two extremes on the lake borders, show sound rock that

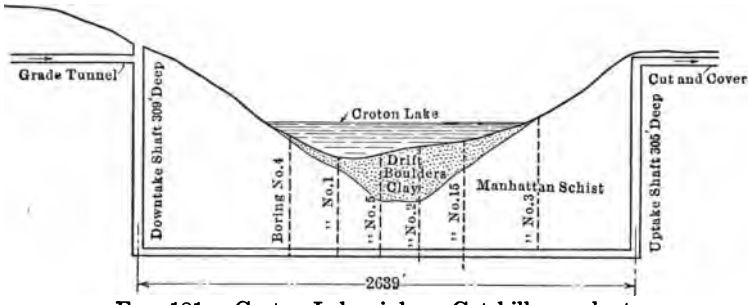


FIG. 181.—Croton Lake siphon, Catskill aqueduct.

comes up in large cores with very high percentage recovery. This is confidently believed to represent the average condition of the rock in this vicinity at the sides of the valley. The central holes, however, Nos. 1, 2, 5 and 15, all show more broken ground. Of these holes, No. 2 is much the most broken, the core recovered being only 14.8 per cent. The pieces are small, and many are smoothed by movement. The hole penetrates a typical crush zone resulting from slight faulting movements, and the low saving is due to the fact that the incipient fractures are not well bound together by mineral changes.

The commonest secondary mineral now filling these crevices is chlorite, and although it may completely fill the crevices it has little binding strength. Any new disturbance or strain readily causes separation along the same original lines. But in spite of the fact that the core is broken into small pieces and shows so low percentage of recovery, it is quite certain that the rock itself is not badly decayed. An examination of one of the most

doubtful looking cores from the lower part of hole No. 1 showed under the microscope little evidence of serious decay. This is believed to mean that underground water circulation is not as abundant as the fractured condition of the rock would lead one to expect. Furthermore, an examination of the cores in greater detail shows beyond question that much of the fracturing is entirely fresh and must have been done by the drill itself. It is certain that the low percentage of recovery is in part due to this cause. The small diameter of the intermediate holes is contributory to the same results. Some allowance must also be made for the difficulty of working a machine from a raft on the lake. Comparison of the cores shows a decidedly higher percentage of core recovery, and presumably therefore of rock solidity in all of the other three holes—Nos. 1, 5 and 15.

Hole No. 2, core recovered	14.8 per cent.
Hole No. 1, core recovered	34.6 per cent.
Hole No. 15, core recovered	36.3 per cent.
Hole No. 5, core recovered	38.9 per cent.

It therefore appears that the last three penetrate rock that is more than twice as good in its capacity to stand drilling disturbance.

In view of the fact that the tunnel wiii undoubtedly be located somewhere below the −75-ft. level, it is really only this lower section that is of vital importance to the project. From the condition of the cores recovered there seems to be much more substantial rock below the −75-ft. level.

The chief elements of uncertainty remaining after the borings have been completed are:

1. The exact extent or widths of the chief crush zones.
2. Their dip and strike.
3. The possibility of others not yet touched.
4. The permeability of the rock for underground water.
5. The supporting strength of such rock in a tunnel of large dimensions.

In spite of the uncertainties enumerated, the conditions are entirely understandable. There is little probability of finding a worse condition than that shown in hole No. 2. The permeability or porosity of these zones is of course unknown. The chief reason for believing that underground circulation is not abnormally heavy is the observation that the joints are well filled with chlorite and that other decay is not at all prominent at the lower

levels. Furthermore, the rock is a crystalline type of rather successful resistance to ordinary solution agencies and therefore may be depended upon to hold its own in its present condition indefinitely. But because of the poor binding effect of the chlorite it is to be expected that blocks will fall from the roof of any tunnel where it passes through a crushed zone. Timbering will be required for protection in places, but the ground will not cave or run. These zones may be expected throughout a total distance of about 700 ft., *i.e.*, the space between No. 1 and No. 15. The chief belt of such ground probably lies between holes No. 2 and No. 5.

Summary

The lowest bedrock is about sea level.

This pressure tunnel will cut only Manhattan schist.

All rock is good ground for such work, except in certain narrow zones where it is crushed.

The extent of such broken ground is not closely delimited, but occurs at intervals for a distance of 700 ft.

The amount of underground circulation is judged to be moderate at −100 ft.

The tunnel should be located deep enough to take advantage of the improved rock conditions shown at about −100 ft. There seems to be no marked improvement below −100 ft. as deep as the drills have gone.

Construction Methods

No difficulties were experienced in driving either the shaft or the tunnel, which were 14 ft. inside diameter and lined with concrete.

The shafts were drilled with 10-ft. cut holes and 8-ft. side and rim holes. The average progress was 13 and 16 ft. for the down- and upshafts respectively.

The tunnel was driven with the top heading and bench method; there were four drills in the heading and two on the bench. Very little water was encountered either in the shafts or tunnel.

Blaw steel forms were used for concreting the shafts and tunnel.

The pressure tunnel was concreted by laying first an invert section 6 ft. wide, then the balance of the lower semi-circumference and finally the arch section. About 25 ft. of lining was laid per day.

Rondout Siphon

The Rondout siphon, a part of the Catskill aqueduct, is 23,608 ft. long between end shafts. For the purpose of expediting work, six working shafts were driven in addition to the uptake and downtake end shafts. The depth of the shafts varies from 370 ft. to 710 ft.

The siphon crosses under Rondout valley at an average depth of about 400 ft. under one-half of the tunnel and 500 ft. under the other half.

Geological Formation[1]

The geological formation of the ground underlaying the Rondout valley is extremely complex, as shown in Fig. 182. Almost everywhere the surface is glacial drift. Where outcrops of bedrock occur they habitually present the unsymmetrical ridge appearance, usually with a more or less sharply marked escarpment on one side and a gentle slope on the other. The strike of these features is in general northeasterly and on the gentle slope in the westerly one.

There are no less than twelve distinct stratigraphic units every one of which will be cut by the tunnel. Their depths vary from 50 to 2000 ft., and the aggregate depth is 4775 ft. The tunnel penetrated chiefly Hudson River slate, Esopus shale, Shawangunk conglomerate, Hamilton shale, also various limestones and sandstone.

These occur in belts in succession more or less regularly from west to east. Most of the formations are quite uniform in the Rondout valley. The Shawangunk conglomerate is probably more variable than any other as shown by borings. Because of this general persistence of formation it is possible to estimate approximately the depth at which any particular lower member lies if some starting point can be identified.

Practical Questions

The chief practical questions to be given as full answers as possible are: 1. At what depth must the aqueduct tunnel be placed in order to be everywhere in substantial bedrock with sufficient

[1] Partly condensed from "Geology from the New York City Aqueduct," by Charles P. Berkey.

THE
FU

cover to be safe? 2. Where are the most critical places, those whose geologic character are such as to demand exploration? And at the same time which sections may be safely left without testing? 3. What is the rock structure and condition, and are there reasons for believing that the tunnel plan is not feasible at this point? If so, where can a better one be found? 4. What is the character of underground circulation of water? 5. What formation will be cut at the different points and which should be favored or avoided wherever possible?

Explorations

Systematic explorations and tests are represented chiefly by drill borings through drift into the rock floor. These were supplemented by two test tunnels for working character of material and a series of tests on the behavior of certain of the drill holes, together with other tests on material.

The question of imperviousness, and closely associated with it that of solubility, is of great practical importance in this particular work. The immense pressure under which the tunnel will be placed in crossing this valley makes it impossible to construct a water-tight lining. Everywhere much depends upon the rock walls to help hold the water from serious loss. Wherever the rock is fairly impervious except occasional crevices or joints it can be grouted satisfactorily. But where a formation is of general porosity this cannot be so successfully done. Even more difficult to handle is the rock wall which is soluble and which, therefore, with enforced seepage may tend to become progressively more porous. That this consideration is not wholly theoretical is shown very forcibly by the Thirlmere aqueduct of the Manchester (England) waterworks. In that case a 3-mile section was built through limestone country, using the same local limestone for concrete aggregate. Although this concrete was mixed as rich as 1 part cement to 5 parts aggregate and the work was well done, excessive leakage reaching a total of 1,250,000 imperial gallons per day was developed within a year. It was found that the limestone fragments of the aggregate were corroded forming holes through the lining of the aqueduct and that these holes actually enlarged outward. In the Rondout valley, the aqueduct cuts no less than six limestone beds in all cases under great pressure.

Test Borings

Some 16,000 lin. ft. of bore holes were made, and the average saving of core, by all machines cutting all kinds of bedrock, was 75.96 per cent. Several borings struck artesian flow of water, discharging from 10 to 30 gal. per min. each.

In addition, to determine the location and thickness of the beds and the general character and condition of the rock from inspection of the cores, serious attempts were made to determine the relative porosity and water-bearing quality of the rock encountered for the following reasons: 1. To determine the probable leakage from the siphon when in operation. 2. To determine the probable amount of water to be handled during construction.

Method of Construction

Driving of the eight shafts started almost simultaneously. As bedrock was overlaid with earth, clay or hardpan, and with sand and boulders in some cases, the shafts had to be timbered and at shafts 1, 2 and 5 concrete caissons were built and sunk down to rock (Fig. 182). Considerable trouble was experienced in sinking shaft No. 2, as the material penetrated was silt and clay, together with boulders. A concrete caisson 2 ft. thick with cutting-edge was provided here. Much difficulty was experienced also in sinking shaft No. 5, the material overlaying bedrock being sand, gravel and boulders, and a concrete caisson had to be provided here also.

In general good progress was made when driving the shafts through rock, as many as 168 ft. of shaft being driven in 1 month through shale.

In driving shaft No. 4 much water was encountered and a very adequate plant was thus necessitated. As many as 710 gal. of water per min. was discharged by various seams, and acid sulphur gases caused much annoyance and a ventilating plant consisting of three pressure blowers was installed, forcing in air through 14-in. pipes.

Driving the Tunnel

A very elaborate plant had been installed, aggregating 22,600 cu. ft. of free air per min. in ten steam-driven, 2-stage, Ingersoll-Rand units. The boiler plant has a total capacity of 2500 H.P. Air was delivered to the shafts through pipes varying in diameter from 12 to 6 in.

The bore ready to receive the concrete lining was approximately 18.5 ft. in diameter, and the concrete lining varied in thickness from 12 to 25 in., 12 in. being the minimum thickness allowed.

The contractor, the T. A. Gillespie Company, endeavored their best to drive the tunnel at a reasonable speed, and good progress was attained, the average being 305 ft. per month per heading and the maximum 489 ft.

The top heading and bench method was used throughout with the driving, there being 4 Ingersoll-Rand drills mounted on columns in the heading and two on the bench. Japs drills were used for trimming close sections. The bench was kept 70 to 75 ft. back of the heading's face, and the heading muck was handled and hauled from the heading over to a timber platform, carried on pipes jacked between the walls of the bore, hence dumped into cars on the tunnel grade.

About 43 per cent. of the tunnel length was timbered, the timbering consisting usually of a three-piece segmental arch carrying 2-in. lagging. Before concreting all timber was removed.

In heavy sections, a five-piece segmental arch timbering set carrying 12-inch I-beams was used, the beams being embedded in the concrete and the timbering being removed as concreting progressed. When driving the heading through High Falls Shale, much trouble was caused by water spouting from bore holes under high pressure. The bore holes had to be grouted under 150 to 200 lb. pressure so as to seal water-bearing seams. A very elaborate pumping plant of 4770 gal. per min. capacity, in 11 units was installed in the tunnel to handle underground water. At one time as many as 200 gal. per min. were pumped against a head of 500 ft.

The driving of the shafts and tunnel of the Rondout siphon was undoubtedly the most difficult piece of tunnel work on the Catskill aqueduct; nevertheless the work was carried on with energy and with success by the contractor.

The preliminary geological surveys and the borings were of great assistance in warning the tunnel crews against possible inflow of water or excessive pressure, although the expectations were surpassed in most instances.

CHAPTER XVII

TUNNELS DRIVEN WITH COMPRESSED AIR

The first application of compressed air in connection with tunnel work was made over a quarter of a century ago; its use, since, has been broadened to such an extent that a large amount of shaft sinking work, foundations for buildings and bridges, etc., is done with the assistance of compressed air.

Nearly all subaqueous tunnels driven under rivers or bodies of water are driven with compressed air, with or without the assistance of a shield. In this book, only bores driven without a shield will be considered.

When driving a tunnel under a stream of water, or through water-bearing strata, the tunnel man has to contend, very often, with a large amount of underground water, flowing under pressure, which finds access into the bore through open seams, or mud seams, in the rock, or through faults, crushed zones, etc.; very often also, sand mixed with water and gravel or boulders is encountered. On account of its fluid state and lack of cohesion, such a material is handled with difficulty only, and, in addition to the timbering used during the driving process, it becomes necessary to sheet all exposed surfaces or walls of the bore, so as to prevent slips, cave-in, etc.

The purpose of compressed air, when used in tunnel work, is to counterbalance or reduce the pressure acting on the timbering or sheeting, and also to keep the bore in a dry condition, for tunnel men to work in. Compressed air possesses also the advantage to dry, to a certain extent, the walls of the tunnel, thus making these more stable or more workable.

Compressed air has been used, without a shield, in connection with the driving of the Milwaukee Waterworks tunnel; the Gattico tunnel in Italy; the Emmersberg tunnel, in Switzerland; the Buffalo Waterworks tunnel; the intake tunnel of the Milwaukee Waterworks; the Colorado siphon of the Yuma Irrigation Project; the Eastview tunnel on the Catskill aqueduct, etc.

Driving Methods

It was many years after its first adaptation to tunnel work that compressed air became popular; for, in order to be effective, its use can be made only under certain conditions. For instance, when the external pressure acting on the tunnel becomes excessive, driving with compressed air becomes impossible, as tunnel men cannot work under high air pressure without taking the risk to be subjected to paralysis, the caisson disease known as "bends." In driving the Gattico tunnel, air pressure did not exceed 16 lb. per sq. in.; in the Milwaukee Waterworks tunnel the pressure varied from 25 to 38 lb. per sq. in. The compressor plant of the Milwaukee Waterworks was designed to supply air under 35 lb. pressure. In the Eastview tunnel, the maximum pressure was 25 lb. In the Colorado siphon, the pressure varied from 27 to 32 lb. In sinking a caisson for shaft 23 of the New York City pressure tunnel, a maximum air pressure of 46 lb. per sq. in. was used, corresponding to a column of water 106 ft. high. In driving the tunnel for the East River Gas Co. the pressure was 52 lb. per sq. in. corresponding to a head of water of 120 ft.

Experiments carried on by Mr. Hersent, a French engineer, demonstrated that a man in good health can work under normal conditions and for a short period of time under a pressure of 77 lb. per sq. in.

When driving a tunnel with compressed air, an air-tight bulkhead, provided with an air lock is built first, closing the bore as shown in Figs. 183 and 184. The bulkhead is usually built of stone, brick masonry or of concrete; when the bore has a small cross section, and when the pressure is low, a timber bulkhead heavily braced and sheeted will answer the purpose. The lock serves the purpose to let the men in and out of the working section, also the materials. Sometimes both a man and material lock is provided as shown in Fig. 184, the man lock being usually smaller than the material lock, and located at the upper part of the bore, so that in case of flooding of the tunnel, a means of escape is thus provided in that part of the tunnel last flooded.

The lock is provided with air-tight doors at each end, and with valves for the admission and exhaust of compressed air. When the bore has a small cross section, two masonry bulkheads are provided, with a space of 20 or 30 ft. between, more or less, thus

forming an air lock, and air-tight doors are provided in each bulkhead.

For the purpose of letting the men enter the air lock, the door on the compressed-air chamber side is kept closed, and that on the free air side is opened. The men then enter the air lock and

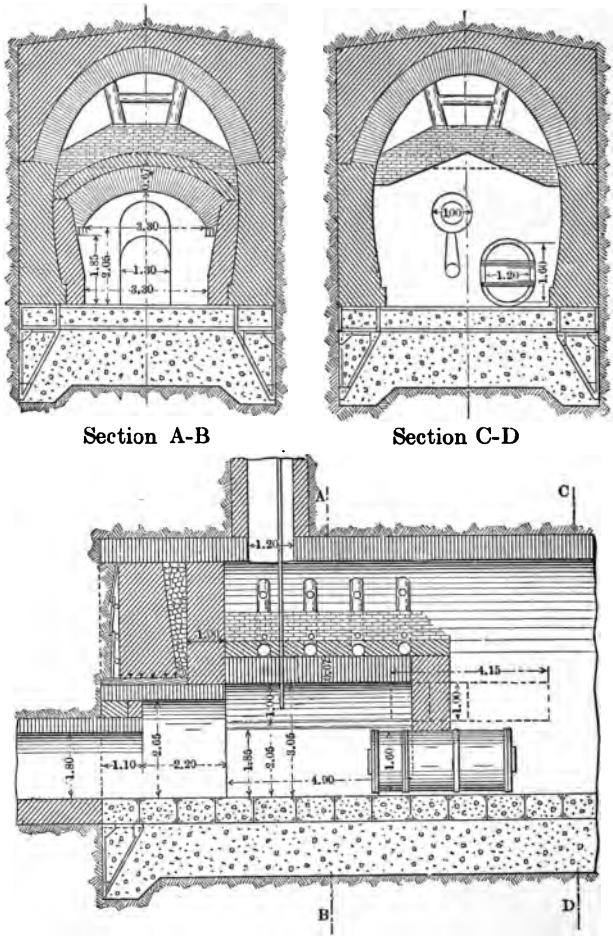


FIG. 183.—Air locks, Gattico tunnel.

the last-named door is closed; compressed air is then admitted slowly into the lock, and when the pressure in the lock is equal to that in the working chamber, the door next to this chamber is opened, and the men step into it. When leaving the working chamber, the operation is carried on in a reversed order, but,

in order to avoid being subjected to the bends, the men stay a certain length of time in the air lock, varying from 15 to 45 min., more or less, and the pressure in the lock is decreased gradually. The higher the pressure the men work in, the longer should be the decompression period in the air lock; also the higher the pressure is, the shorter the working shifts are.

The regulations of the Compressed Air and Foundation Workers' Union are as follows:

Pressure, pound per sq. in.	Working hour, total	Worked per shift, hours
1 to 22	8	½ hr. out for lunch.
22 to 30	6	3 on; 2 or 3 off; 3 on.
30 to 35	4	2 on; 4 off; 2 on.
35 to 40	3	1–½ on; 4–½ off; 1–½ on.
40 to 45	2	1 on; 5 off; 1 on.
Over 45	1 hr. 20 min.	As arranged.

As work progresses, the air lock is shifted forward, or then left open, and a second lock is built nearer to the working face. Sometimes also, work in the heading section is carried under high pressure, and that in the section between the locks, under low pressure.

The Gattico Tunnel

The Gattico tunnel on the line connecting Santhia with Borgomanero, in Italy, is a single-track bore 10,548 ft. long, driven

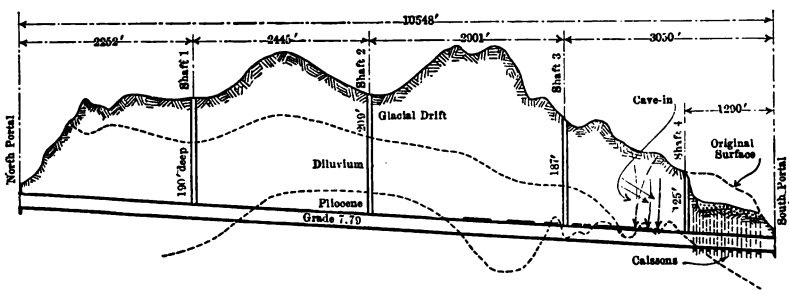


FIG. 185.—Longitudinal section, Gattico tunnel.

on a 7.79°/00 grade. There are two curves in the tunnel, near the portals, each with a radius 1970 ft. long, and another curve near shaft two, Fig. 185, with a radius 3280 ft. long.

The maximum depth overlying the tunnel is 280 ft. and the average depth is about 200 ft.

The material expected to be encountered was glacial deposit, consisting of sand, and boulders, reasonably dry. This supposition was correct except that on the south side quicksand was encountered together with water under pressure. A similar condition prevailed between shafts 4 and 3.

For the purpose of increasing the points of attack, three shafts were driven, and later on, one more.

Construction Methods

Driving was started in May, 1902, at the north side, using the Belgian method. The material penetrated was hard sand with clay; little water was encountered first. As driving progressed, however, sand, gravel and water were encountered, thus necessitating much pumping. As work progressed, 35 cu. ft. per min. had to be pumped against the grade. It took 13 months of hard work to drive 1725 ft. of tunnel, *i.e.*, an average daily progress of 4.9 ft.

Driving the Shafts

The shafts have an elliptical cross section and their vertical axis is located 39.4 ft. from the tunnel axis. They were lined with masonry throughout.

Shaft No. 1 was driven through dry material over a length of 50 ft.; then it penetrated fine sand and finally quicksand together with much water. The driving progress was only 1.5 ft. per day. This shaft was driven about 10 ft. below the tunnel grade so as to provide room for a sump. The tunnel heading was then driven toward the north portal. The material penetrated by the heading toward shaft No. 2 stood well, so that the average progress was about 8 ft. per day.

More trouble was experienced in driving shaft No. 3 on account of quicksand and water. It took 7 months to drive the first 80 ft., and 2 months for the last 95 ft. Headings were then driven from the bottom of the shaft toward shaft 2 and toward the south portal. Little water was encountered first, and the pumping plant of 300 gal. per min. handled all underground water adequately until heavy rains caused the flow to exceed the capacity of the pumps, thus flooding the tunnel, and water rose some 90 ft. in the shaft. After hard work, the pumping plant was put in operation and later on, its capacity was increased.

Driving then became very difficult; it was necessary to timber and line the tunnel immediately on account of the soft nature of the material penetrated and the enormous ground pressure. The difficulties became such between shaft 2 and 3 that it required as many as 17 days to build a rind of masonry lining 20 ft. long, at a distance of 750 ft. from shaft No. 2. Finally the timbering in the heading yielded under the pressure, over a length of 60 ft., that is, the distance between the heading and the masonry, and the heading was filled with quicksand. In order to avoid another cave-in, a masonry bulkhead was built at the last ring of the masonry lining and a side drift was driven some distance away from the tunnel so as to meet the heading driven from shaft 2.

The heading driven from shaft 3 toward the south portal met with difficulties, when a first cave-in of quicksand caused the ground at the surface above the tunnel to sink 23 ft. over an area of some 4000 sq. ft. After the heading had been cleared up, work was resumed, but two more cave-ins occurred soon again. Much water was encountered and the capacity of the pumping plant had to be increased materially. Driving operations were then stopped and a heavy masonry bulkhead was then provided 1000 ft. from shaft No. 3.

Driving was then resumed; the material penetrated was quicksand, large granite boulders and water. Several cave-ins occurred again. It became necessary to line the heading with masonry as work proceeded. Finally driving was stopped, and at a distance of 1425 ft. from shaft No. 3 a drift was driven, perpendicularly to the tunnel axis, over a distance of 48 ft., then parallel to the tunnel axis over a distance of 227 ft., and then again toward the tunnel axis where the drift met the heading driven from the south portal.

Driving from South Portal

The difficulties met in driving this side of the bore were, by far, in excess of those heretofore met with. As stated before, the Belgian method of driving was used, a small drift being driven first at the arch, then widened out and the arch masonry laid first, before the bench had been excavated.

The first 61 ft. of tunnel were driven and lined with difficulties; then 137 ft. of tunnel arch were driven and lined with masonry, pending the excavation of the bench; but enormous pressure soon

caused the whole 137 ft. of masonry lining to sink so far down that it had to be rebuilt entirely, although the arch masonry had purposely been built 3 ft. higher than normal elevation, in anticipation of possible settlements.

The reconstruction of the lining is illustrated in Fig. 186. In addition to the heavy timbering, brick masonry had to be provided temporarily in the bore and then removed.

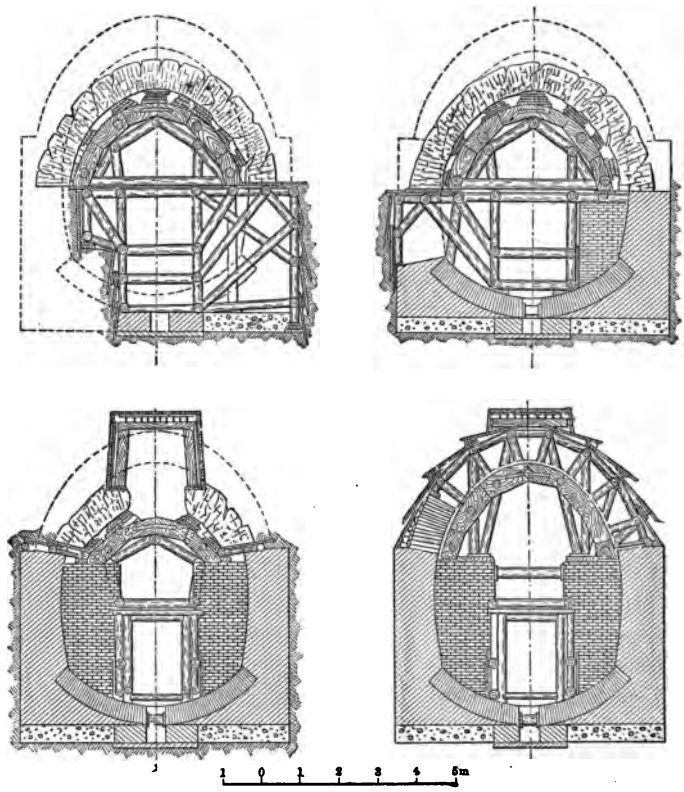
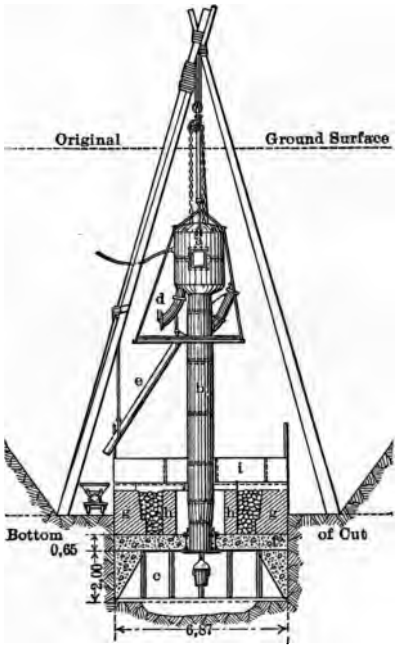


FIG. 186.—Sequence of reconstruction after failure of masonry lining, Gattico tunnel.

It was then decided to sink shaft No. 4 in order to increase the points of attack. It was sunk down to tunnel grade, but quicksand and so much water were encountered that it had to be abandoned. Another shaft was sunk nearby with compressed air, down to tunnel grade, but when the iron lining around the masonry was cut open for the purpose of attacking the tunnel head-

ing, a cave-in occurred filling in the caisson with sand, water and boulders, and the iron lining collapsed; this shaft was also abandoned.

Various driving methods were then suggested, such as to change the alignment of the tunnel axis, or to use a shield and compressed



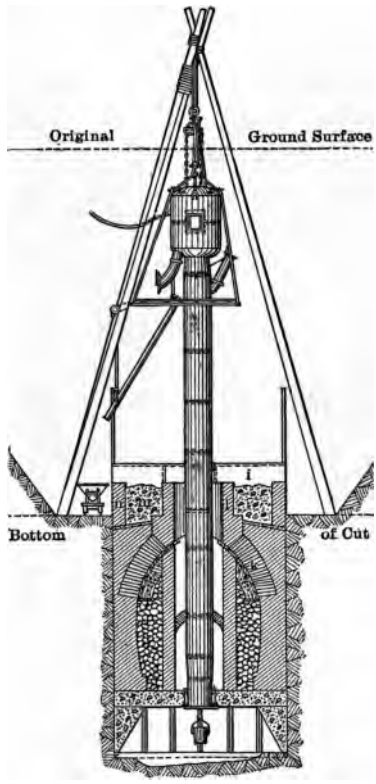


FIG. 187*a*. FIG. 187*b*.

FIGS. 187*a* and 187*b*.—Method of sinking caissons, Gattico tunnel.

a, air lock; *b*, caisson shaft; *c*, working chamber; *d*, material lock; *e*, material chute; *f*, concrete deck; *g*, tunnel side walls foundations; *h*, shaft masonry; *i*, shaft iron lining; *k*, tunnel arch masonry, *m*, weight; *n*, shaft masonry walls.

air; finally it was decided to sink caissons from the surface down to grade as shown in Fig. 187, *a*, *b*, and *c*.

First, the original ground surface was excavated and graded so as to provide a seat for the caissons as shown in Fig. 187*a*. Eleven caissons 56.7 ft. long and 22.5 ft. wide were sunk about 33 ft.

without compressed air and then 22 ft. more with compressed air, their location being as shown in Fig. 188.

Caissons 1 and 2 were sunk first; much difficulty was experienced in connecting these, and especially in completing the section

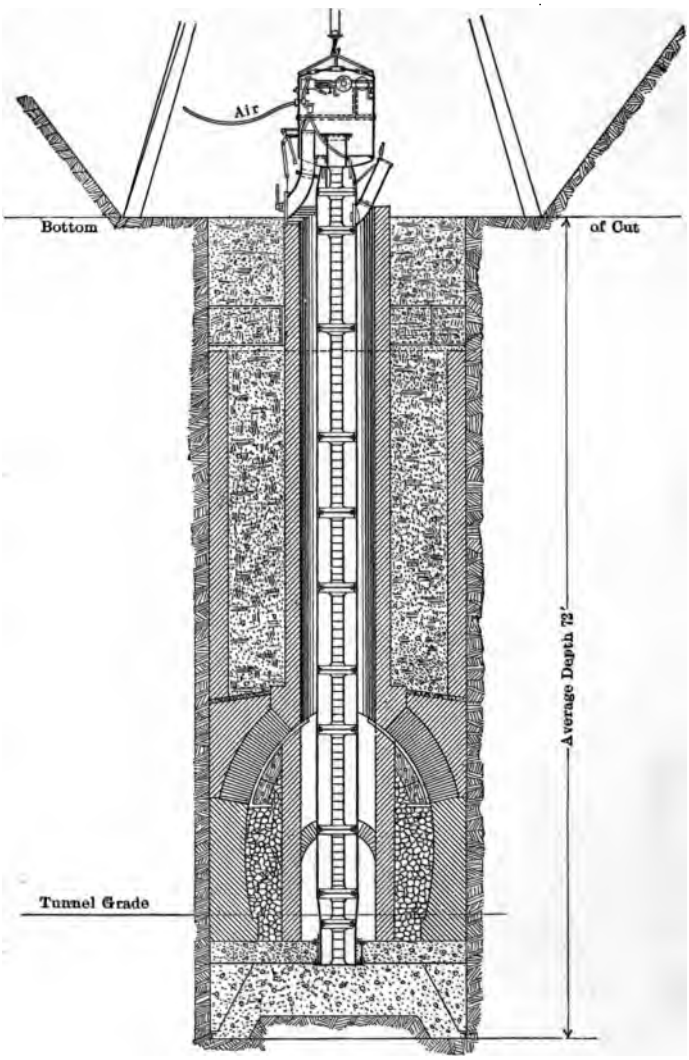


FIG. 187c.—Method of sinking caisson, Gattico tunnel.

between caisson 1 and the finished tunnel section toward the south portal, as the material penetrated had been thoroughly loosened by sinking the caissons.

The caisson method proved successful, but slow and rather costly, and it was then decided to drive the tunnel horizontally with compressed air, from caisson 2 toward shaft No. 3. Caissons 4 to 10 and *A* had not yet been sunk.

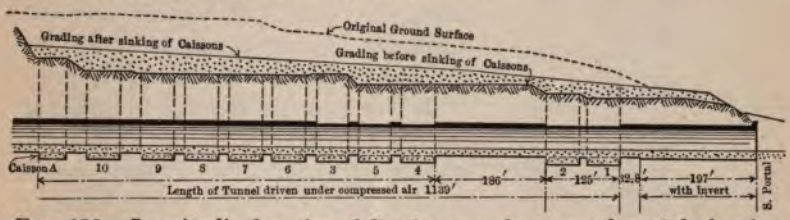


FIG. 188.—Longitudinal section of Gattico tunnel near south portal, showing location of caissons.

A heavy masonry bulkhead was then provided in caisson No. 2 with an air lock 5.25 ft. diameter and 11.5 ft. long; driving was car-

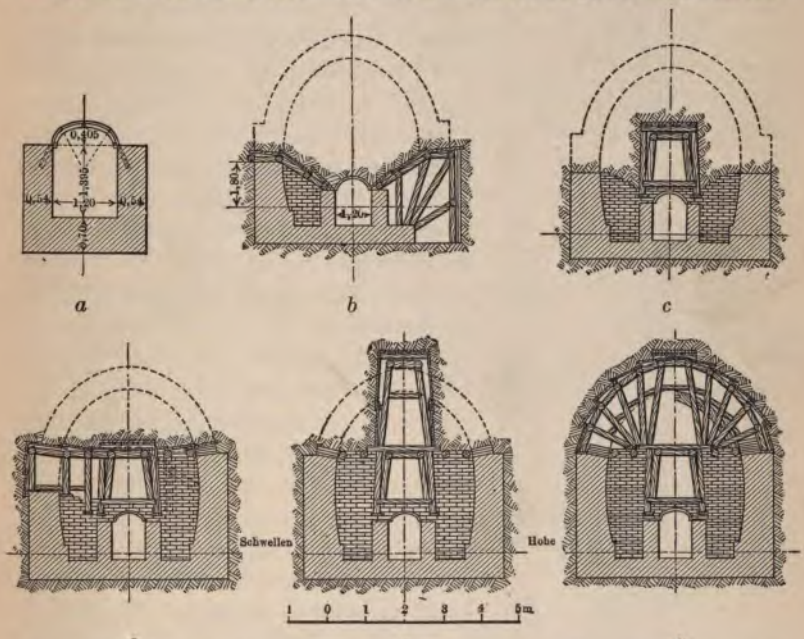


FIG. 189.—Method of excavating, timbering and lining, Gattico tunnel.

ried on under air pressure of 10 lb. per sq. in. A bottom heading was driven first and immediately lined with stone masonry. First, stone masonry was used for the headings arch, but later on,

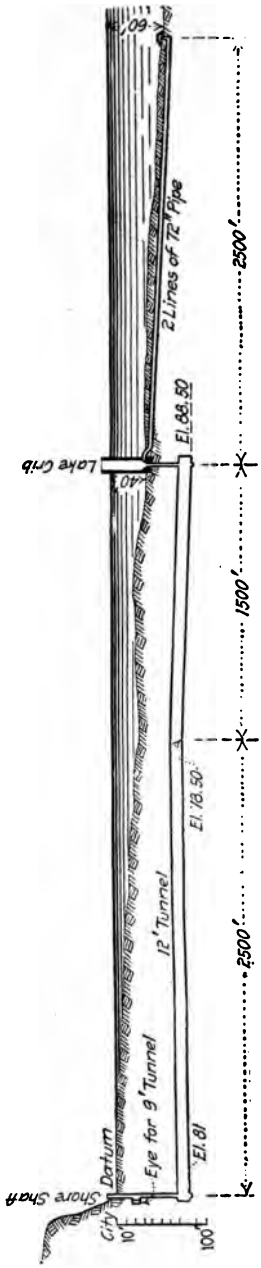


FIG. 190.—Profile of Lake intake tunnel, Milwaukee, Wis.

structural steel ribs were found to answer the purpose desired. Thus 75 ft. of heading were driven and lined as shown in Fig. 189, *a*. The heading's face was then bulkheaded and the bore was enlarged, timbered and lined as shown in Fig. 189, *b*, *c*, *d*, *e*, and *f*. This work was accomplished under air pressure of 10 to 12 lb. per sq. in. As the method proved to be slow, caissons 3, 4 and 5 were then sunk. During the driving of these, the tunnel section between caisson 2 and 4 was carried close to caisson 4 which was still in course of being sunk; at this point, the tunnel was bulkheaded with a heavy masonry wall, capable to resist the pressure from air escaping from caisson 4, under construction. After this caisson had been sunk to grade, it was connected with the completed tunnel section. Caissons 6 to *A* were then sunk with an air pressure of 10 to 16 lb. per sq. in.

There still remained about 182 ft. of tunnel to be driven toward shaft No. 3. A masonry bulkhead with air lock was provided in caisson *A*, and a bottom heading was started on grade first, but a stratum of impervious material was struck, sloping toward the heading driven south of shaft No. 3, and the heading was subsequently driven on a slope until it reached the heading referred to above. This heading had to be heavily timbered and lined throughout with stone masonry. It was then enlarged to the springing line, and the arch masonry was laid. The side walls were then built downward to grade. All this work was accomplished under compressed air.

The whole tunnel was driven in 3 years and 9 months. $100,000 were spent for timbering material alone. No death resulted from any accident throughout the driving period of the shafts and tunnel.

Tunnel Intake for Milwaukee Waterworks

The work consists of a 12-ft. tunnel, 80 ft. below datum, extending 4000 ft. northeast from a shore shaft, to an intake shaft at a crib, from which two 6-ft. steel pipes will extend 2500 ft. to submerged cribs in water 60 ft. deep, as shown in Fig. 190. The contract price for sinking the short shaft was $89,700, and that for the tunnel $450,000.

Borings

When the preliminary engineering and locations were decided upon, borings were made to determine the strata along the line of construction. The borings made for the old intake were used also in order to better study the strata. It was found that over the lake bottom along the entire length of the tunnel there is a layer of clay of an average depth of about 5 ft. Below this was found a layer of hardpan consisting of cemented gravel. This layer is 16 ft. thick; underneath it were found black and brown shales interlaid with thin layers of soapstone.

Having found a good covering over the proposed tunnel, it was decided to build as close to the surface as possible to minimize the air pressure in the tunnel and a depth of 80 ft. was selected. This will keep the tunnel in brown shale and at the lake end the roof will be in black slate.

Shore Shaft

The shaft is 15 ft. diameter and 80 ft. deep from the datum line (lake level) to the floor of the tunnel opening, or 85 ft. to the bottom of the sump.

The shaft is lined with concrete 18 in. thick. For the upper end, a circular shell was formed by driving sheet piling 45 ft. long, and within this the excavation was commenced. The shaft timbering was octagonal in plan, with 80-in. sides and an inside diameter of 19 ft. Steel forms were used for the concreting and after the lining was completed, a two-cage elevator was installed as part of the working plant for the tunnel.

The material penetrated was clay and hardpan at the upper end, and the greater part of its depth is in brown shale with some soapstone layers. Very little water was encountered. No concreting was done until the entire shaft was excavated.

Intake Tunnel

The intake tunnel is of circular section, 12 ft. diameter, with a length of 4000 ft. between the short shaft and the lake shaft. The borings indicate that below the surface stratum of red clay are hardpan and soapstone, underlaid by a thick bed of brown shale. The shale is hard but shoots easily in blasting. As soon as exposed to the air, however, the material begins to flake and disintegrate, and in contact with water it soon turns to mud. Very little water was found and only a few pockets of gravel; some gas was encountered.

The concrete lining is 18 in. thick, and the masonry work was kept about 80 ft. from the heading.

To provide for carrying on the work under compressed air, if water or loose material should be encountered, an air lock has been installed 75 ft. from the shaft and provision made for carrying 35 lb. pressure. The lock is shown in Fig. 184; the material lock is 7 ft. diameter and 21.5 ft. long, with a track for the cars and a door 4 by 4 ft. Above this lock there is a man lock 4 by 12 ft.

The excavation is carried down to the level of the base of the side walls. These walls are built first and are followed by the roof arch. They are built two or three days ahead of the arch and are kept about 30 ft. in advance of the latter. The work is carried on in two 10-hr. shifts.

The Eastview Grade Tunnel

This bore on the Catskill aqueduct is 5455 ft. long; it was driven from the north and south portals and from a shaft 90 ft. deep, sunk to grade, about 2040 ft. from the south portal. The contract price for rock excavation was $5.50 per cu. yd., but as it was anticipated that part of the tunnel would be driven with compressed air, a special unit price of $6 was allowed for excavation in compressed air.

In general, driving proceeded without unusual difficulties from the south portal to beyond 350 ft. from the shaft, and from the

FIG. 167.—Method of timbering heading, American method.

FIG. 184.—Man and material locks, Milwaukee Waterworks tunnel.

(*Facing page* 216.)

Fig. 191.—Concrete bulkhead and lock, Eastview Grade tunnel.

north portal to about 1850 ft., when bad ground was encountered in both headings. The materials encountered consisted of wet sand and boulders and clay. Work in the north heading was stopped and driving proceeded from the south heading where heavy timbering was required. It consisted of five-segment arch sets placed side by side. Soon, however, signs of weakness and settlements became apparent, and it was decided to carry on driving with compressed air.

A concrete bulkhead, Fig. 191, was built across the bore 260 ft. from the shaft; the bulkhead was provided with a man and material lock. A bulkhead with air lock was also provided in the completed part of the tunnel section driven from the north portal so as to keep up the air pressure when the headings would meet. As a matter of fact, the bulkheads were not removed until the bad section of the tunnel was concreted.

Driving of the bad section was made very difficult on account of the heavy timbering required to resist ground pressure. It consisted of 12 × 12-in. timber sets, placed 14 in. center to center 2 × 12-in. planks between, so that the timbering was continuous. To carry the roof load, a five-segment arch set was used, and to resist upward pressure of the floor a two-piece set was used with a downward rise of about 10 in. In addition, transverse bracing was provided between the wall plates and in the center of the posts. The center segment of the roof arch was also supported by vertical posts.

Driving proceeded under a maximum pressure of 25 lb. per sq. in. The top heading and bench method was used throughout, air drills being used in the section driven in free air and electric drills in the section driven in compressed air. In the bad section, side drifts were driven first for the wall plates, then the material between the drifts was taken out and finally the bench.

The bore was lined throughout with concrete.

CHAPTER XVIII

MISCELLANEOUS TUNNELS

METHOD EMPLOYED IN DRIVING THE TUNNEL AND SHAFTS OF THE NEW ST. LOUIS WATERWORKS[1]

The tunnel here considered is a part of the waterworks improvements for the City of St. Louis. It runs from the present pumping station at the Chain of Rocks plant to the new intake tower in the Mississippi River. At the pumping station there is a large shaft for the screen chamber and a connection from this to the present pump well. From the screen chamber the main tunnel runs on a descending grade toward the river at about a 6 per cent. grade, for a distance of about 537 ft. to a drainage shaft. This short section of land tunnel has a sharp curve near the screen chamber.

All the tunnel work was done from the drainage shaft, Fig. 192, and the plant for the work was located there. The shaft is circular and 12 ft. inside diameter in earth and 10 ft. in rock. As 32 ft. of the shaft was in earth and the bottom 14 ft. of that in quicksand, a concrete caisson was used for sinking it down to rock. A cutting edge made of steel plates and angles was built first and concrete was then poured for the first 5-ft. section, and the forms for the second section were placed immediately after. The concrete was carried up for 20 ft. in this manner when all the forms were removed and the excavation started inside the caisson. Vertical timbers were placed against the outside of the concrete at four places around its circumference braced solidly and plumbed up exactly to keep the caisson vertical. The progress through the lower 18 ft. of earth and sand was very rapid, as much as 8 ft. of shaft being excavated in an 8-hr. shift. When the caisson had reached the rock it was caulked with wooden wedges and oakum between the caisson and the rock. About 4 ft. of the shaft was then excavated in the rock and a collar concreted in it reaching from a point about 2.5 ft. below the top of the rock to a point about 2.5 ft. below it. This collar was 11 ft. inside diameter and when the concrete lining in the rock section of the shaft is placed

[1] Condensed from a paper by C. H. Hollinsworth.

it will be 10 ft. inside diameter covering the collar completely as the lining will reach up to the top of the former.

Drilling was carried on with four *C*-110 Ingersoll-Rand drills mounted in pairs on two 4.5-in. bars 10 ft. long, each bar being equipped with two arms. It was desired to do all the drilling in one shift and the mucking on the other two. The two bars were set up in the shaft as far apart as possible and all holes were drilled from the one setting. As a usual thing 6- or 7-ft. cut holes and 4- or 5-ft. side round holes were drilled. Working on this system and with even a fairly dry shaft a progress of from 4 to 6 ft. per day could be maintained. As it was, however, the progress from start to finish on the rock section averaged about 2.6 ft. per day, not allowing for lost time. Exclusive of lost time the daily progress was 4 ft. per day.

When the shaft had been sunk to tunnel grade two shots were taken out of each tunnel heading after which the sump was shot out. Later when a short distance of tunnel had been driven each way the small drainage tunnel was started. The two main tunnel headings were each

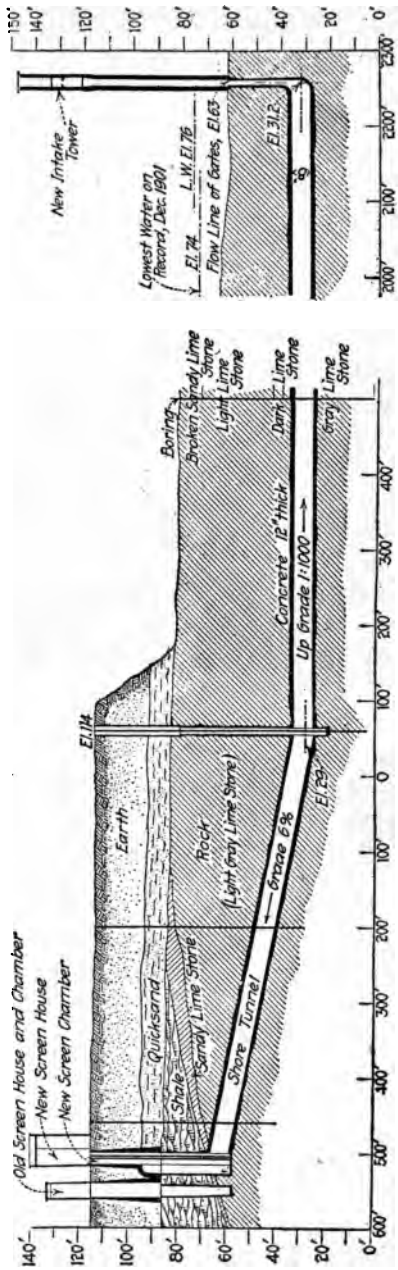


FIG. 192.—Profile of new intake tunnel for the water supply of St. Louis, Mo.

carried in about 200 ft. and the drainage tunnel about 50 ft. before the cages were installed.

For sinking the shaft, round iron dump buckets were used, holding about ¾ cu. yd. These were handled by a stiff-leg derrick with a 50-ft. boom and the spoil was dumped near the shaft. To supply air a 900 cu. ft. per min. capacity two-stage Norwalk air compressor was installed with a 3 × 14-ft. receiver. To supply steam for the compressor, cage hoist and pumps, three 75-H.P. locomotive type boilers were used. A No. 2 Root reversible blower was installed in the house with the hoist engine. From this blower, a 10-in. pipe led to the top of the shaft where it branched into two 8-in. pipes. This pipe was made of No. 22 gauge galvanized iron, both riveted and soldered at all joints. The pipe was made up in 15-ft. lengths with light malleable flanges at each end, and in joining the sections together, heavy roofing paper was used for gaskets.

For handling muck from the headings to the shaft a 3-ton, 24-in. gauge, General Electric Co. storage battery electric locomotive was used. This locomotive had two sets of batteries so that one could be charging while the other was in use on the car. The batteries were changed every 8 hr. Electric current at 2300 volts was obtained from the city and transformed to 220 and 110 volts for lighting purposes and for charging the batteries a standard mercury arc rectifier was used taking 220-volt A.C. current on its primary side and delivering 110-volt D.C. current on its secondary side as the latter was what was used for the batteries.

Drilling and Blasting

Several methods of drilling and blasting were tried, and finally the gangs drilled a center cut, as shown in Fig. 10, of eight holes, four on each side, a breakdown hole above the cut, one center and two rib dry holes and eight side round or trimming holes, making twenty holes in all. Two 4–½ columns 7 ft. long with double screws and with two arms on each were used for mounting the drills.

When getting three shots per day or one per shift, the gang came on shift just after the previous shift had finished shooting. They mucked out, set up the columns and machines, drilled a round and shot it. The rock encountered was generally a hard limestone with occasional streaks of soft limestone. The rock

drilled well in general. All shooting was done with a 220-volt A.C. lighting current from a switch which was kept from 600 to 800 ft. back from the face of the heading.

All drill steels were sharpened with a Leyner drill sharpener, there being one blacksmith and a helper on the day shift only. They handled from 120 to 200 pieces of steel per day, and did all general work besides.

Mucking

The mucking was done at all times by a muck foreman and a gang of six to eight muckers in each heading. With three shots per day five or six men were enough to handle the muck and keep the track in shape. In the heading ⅜-in. boiler plate were laid down before each shot, covering the bottom of the heading for its full width and back for a distance of 25 ft. This made the shoveling easy and the muck cars could be pushed up on these plates. The number of cars loaded in one 8-hr. shift ran from 40 to 65, and afterward it ran about 55 to 65 cars.

General

On the 8 months work there were no accidents with powder and no fatal or even serious accident.

The tunnel was too short in length and of too cramped and unhandy cross section to get up the maximum speed which could otherwise have been attained. In addition, the east heading under the river was on an extremely flat grade and gave much trouble from water, even when the volume of the latter was not great, as it would back up in the heading and cover the track, making it hard to get the holes drilled in the bottom of the heading and putting the electric locomotives out of business, as it could not be run if there was even a few inches of water over the track. On the other hand, the grade in the west heading was over 6 per cent. and it was extremely difficult to handle loaded or even empty cars on that grade.

The best progress made in one day was 29.1 ft. and for a month of 29 days 744.7 ft.

Relining the Mauvages Tunnel on the Marne Ship Canal

The removal of the old masonry lining from the Mauvages tunnel on the Marne canal and its replacement by a thicker

concrete shell have presented unusual construction problems on account of the necessity of keeping the canal open to traffic at stated intervals.

The tunnel is driven through compact blue marl rock quite hard when first taken out, but subject to rapid deterioration under the influence of air and water. In the original construction the lining was built 12 in. thick uniformly over the arch and side

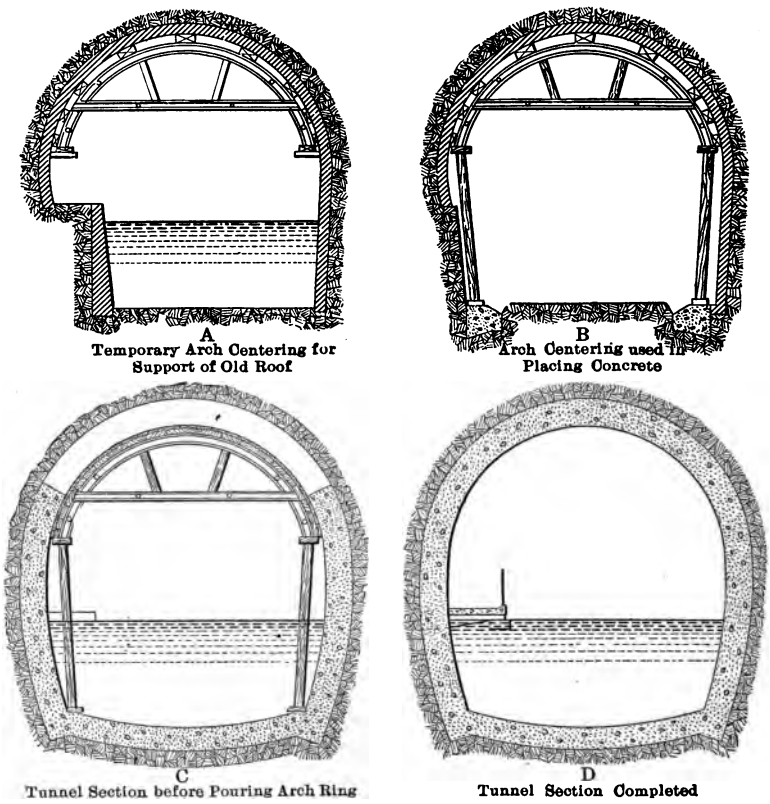


FIG. 193.—Method of reconstruction, Mauvages tunnel.

walls, no lining being provided for the invert section. This plan was adopted on account of the apparent excellent quality of the rock through which the tunnel was driven. Since that time through natural causes, a general loosening of the rock developed, and these changes have resulted in subjecting the lining to unusual and excessive strains. From time to time

repairs have been made at such points as showed evidence of failure, but after a recent examination it was decided that such make-shift measures would no longer answer and that the whole tunnel would have to be relined.

In the new work it was necessary to preserve the same section as obtained with the old lining in order to provide the required clearance for the largest type of canal boat passing the tunnel. This section, shown in Fig. 193, *C*, *D*, has a circular arch with an inside radius of 12 ft. 10 in. with two side walls built on a curve of 38 ft. radius and a circular arc forming the invert line. The arch ring and side walls have a uniform thickness of 2 ft. 8 in.

As the new concrete lining is thicker than the old one, it was necessary to remove considerable material, and in carrying out this part of the work the roof was held up by means of steel arch trusses. These were placed while the canal was still full of water, and they were spaced about 6 ft. center to center and in some cases 3 ft. where pressure was greater.

The portion of the canal below water line was first lined, and in doing this work it was necessary to remove the water from the working sections. This was accomplished by dividing the canal into a series of zones about 600 ft. long, isolating these by means of cut-off caissons. The tunnel was pumped between the caissons and construction was carried on as in a cofferdam. In order to do this, concrete piers or gate heads were built first, about 600 ft. apart in the tunnel. These were 28 ft. long and they were provided with grooves in which the caissons slid, together with four vertical side recesses in which were placed the flexible fittings used in connecting the caisson pumps. This part of the work was carried on during winter, when navigation is impossible on account of ice in the canal.

Caissons and Exhaust Piping

The floating caissons, Fig. 194, which closed the openings between the concrete heads were made of steel plate; they were 28 ft. long and 9 ft. wide. They were towed in place and sunk with water ballast. On each caisson there is a top deck on which are placed two 14-in. centrifugal pumps, each with a discharge capacity of 4500 gal. per min., and a smaller 6-in. centrifugal pump. The former was used for pumping out the working

zones, while the latter is designed to keep the tunnel dry after the first pumping out. This pump was also used to pump out the water ballast from the caissons. Both pumps were electrically driven.

Construction Methods

In conducting the work so as not to interrupt the use of the canal, the caisson and material boats were towed behind the usual train of canal boats, the latter being towed by a steam tug. The caissons are then placed in position and sunk. About 1 hr. was required to unwater a working section. At the end of the day the caisson gates are opened thus admitting water into the working sections again. The caissons are then pumped out and with

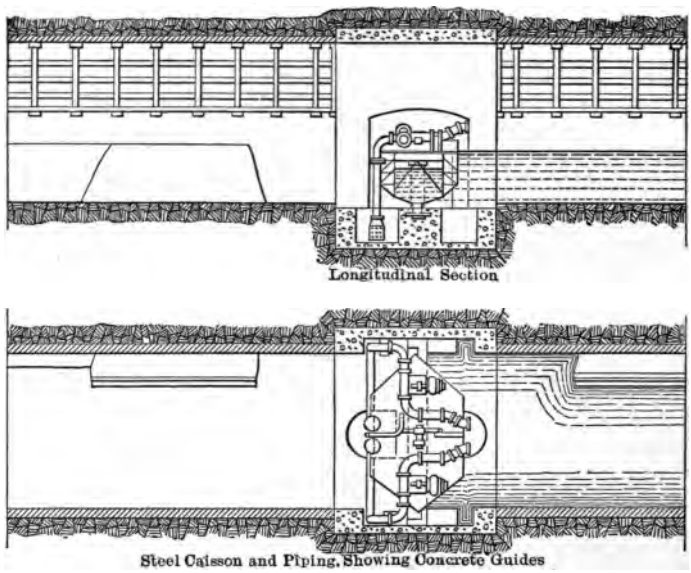


FIG. 194.—Caisson used in relining Mauvages tunnel.

the material barges are towed out of the tunnel to make way for the canal boats on their return trip.

After the arch trusses are placed, the old towpath is demolished and concrete foundations are placed on each side of the tunnel. The walls are built in sections from 12 to 20 ft. long, the concrete being placed during periods when the canal traffic is suspended. These periods last in general about 40 hr., thus giving an interval of between 20 and 30 hr. subsequent to the placing of the concrete

before water is admitted into the working zone. Thus concrete had sufficient time to harden enough so as not to become injured by the action of water. The invert was laid in short sections, depending on the nature of the ground. Reinforced concrete brackets were then built into the tunnel walls for the purpose of carrying the towpath.

When the work below water had been completed, the arch concrete was laid. This was accomplished by first tearing down sections of the old lining over a length of 12 to 20 ft., where the nature of the rock was such as to warrant such treatment. At sections subjected to unusually heavy loads, the length was only 6 ft., and the haunches of the arch were built out on either side together with the side wall, for about $\frac{1}{6}$ of the span. The concrete was then placed over the remaining section of the arch. The work involves about 140,000 cu. yd. of excavation, 118,000 cu. yd. of concrete masonry of which 42,500 yd. lie below water level.

A Heavy Reinforced Concrete Railway Tunnel

One tunnel on the Cleveland Short Line presents some interesting features, having been built as an open cut and then backfilled. The bore has an extremely heavy lining of reinforced 1 :2 :4 concrete. It is 775 ft. long, passes under numerous railway tracks and under a site to be occupied by a new plant of the American Steel and Wire Co., where heavy machinery would be operated, and in order to prevent injury to the tunnel by the shocks and continued vibration a very thick concrete lining is used, heavily reinforced by steel bars. The cut here is in gravel and water-bearing sand.

The tunnel is of horseshoe shape 25 ft. wide at the floor and 30 ft. 6 in. at the springing line, with a roof radius of 15.25 ft. and a height of 25 ft. 9 in. at the middle or 23 ft. 9 in. above the rails. The cross section and the arrangement of the reinforcement are shown in Fig. 195. In the heaviest section of the tunnel, the lining is 5 ft. 3 in. thick at the arch and 6 ft. 6 in. at the center of the floor. Toward one end, the thickness at these points is 4 ft. 9 in. and 5 ft. 9 in. respectively. The steel bars are laid near the inner and outer faces of the concrete and 4 in. from the surface, except that on the inner face of the arch this distance is increased to 8 in. to insure ample protection for the steel after erosion of the concrete by the blast of the engines. The longi-

tudinal bars are used only in the end sections. In the floor there is a double layer of bars 4 in. and 10 in. from the surface, while the sides of this massive floor slab are reinforced by vertical steel stirrups as shown. In the lighter sections of the lining an additional set of transverse bars is used at the crown as indicated by dotted lines. Most of the reinforcement consists of corrugated bars ⅜ in. square.

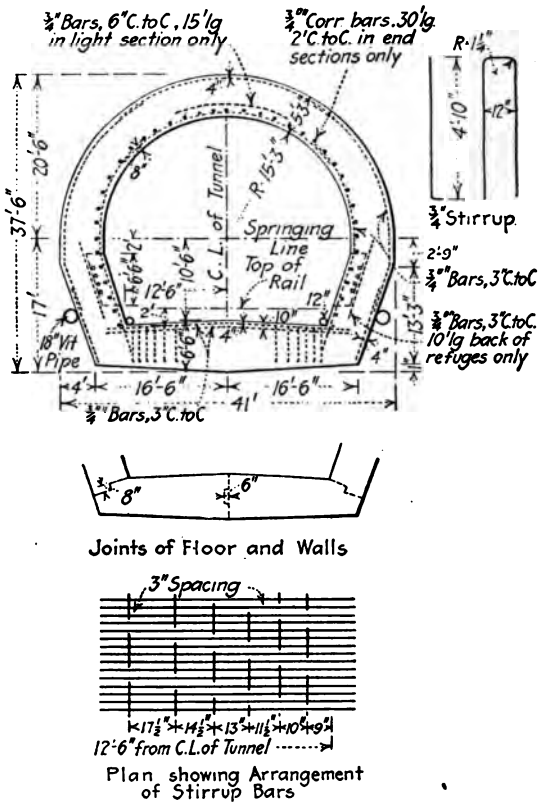


FIG. 195.—Tunnel with heavy reinforced concrete lining.

The floor slopes from the center to the sides, where 12-in. drain tiles are laid in the ballast, and on the outside are two lines of 18-in. drains, which extend through the portals. All these are vitrified pipes. To accommodate signal, telegraph and other wires four lines of 4-in. wrought-iron pipe, spaced 12 in. apart, are embedded in the concrete on each side of the tunnel. On each

side also there are refuges 50 ft. apart; these are 2.5 ft. wide, 2 ft. deep and 6.5 ft. high.

The concrete lining is built in lengths of 30 ft., with tar-paper expansion joints between them, and the longitudinal bars of the end sections are therefore 30 ft. in length. It was required that the exposed surfaces should have a dense and smooth face and the other surfaces should not show honeycombing. In the construction of the lining, the floor was built in two parallel parts connected at the middle by a key or tongue and groove; the width of this is 6 in. and its depth is one-third the floor thickness. The side walls also are recessed into the floor for half their width and to a depth of 8 in., thus giving a shoulder to resist external thrust.

The concrete was mixed at a stationary plant and delivered by dump cars on narrow-gauge industrial tracks. For the floor the concrete was dumped directly from the cars. For the side walls the bodies were lifted by a locomotive crane and dumped into the forms. For the roof the bodies were lifted in the same way, but the concrete was dumped into small push cars running on a track laid over the forms on the center line of the tunnel.

Highway Tunnel Carrying Heavy Loads

The Corliss Street highway tunnel in Pittsburg and its approaches involve heavy concrete roof arches connected to the side walls through tongue-and-groove joints. The arches carry large live loads. The side walls and footings are made extra heavy on account of the very poor quality of the supporting rock. At one point the height of the tunnel roof was increased to reduce its horizontal thrust. The tunnel is 447 ft. long. The foundations rest on varying strata of soapstone, sandstone, shale and clay, some of which are of very poor quality, making it necessary to use some very large wall footings. A plan and longitudinal section of the tunnel are shown in Fig. 196.

General Design and Conditions

The greater portion of the tunnel passes under the main lines of the Pittsburg, Cincinnati, Chicago & St. Louis and the Ohio Connecting Railroad, and its roof is designed to provide for the heavy loading from the tracks of these roads. The first of these

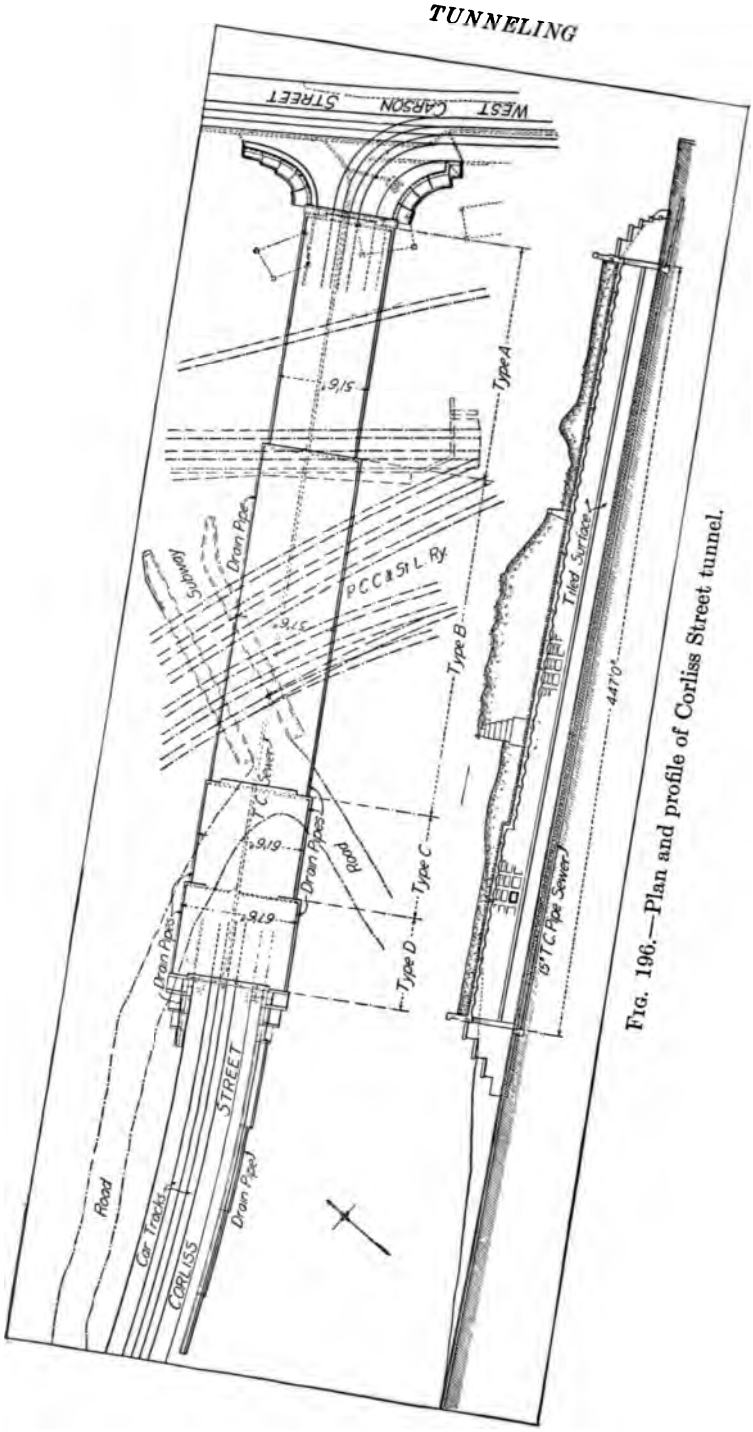


FIG. 196.—Plan and profile of Corliss Street tunnel.

roads has its tracks located on an embankment with a heavy stone retaining wall, through which the tunnel passes, and that part of the wall over the tunnel is supported by the tunnel arch. The latter has a clear span of 41 ft. 2 in. and the concrete side walls are modified to form several different sections, corresponding with the variations in the strata encountered. Above the springing line the arch roof has rectangular molded panels sunk into the concrete, and between the coping and granite baseboard the vertical walls are wainscoated with 6 × 6-in. vitrified tiles. The upper surface of the arch is waterproofed by the membrane system. Drainage is provided for by a 1-ft. layer of gravel placed on top of the waterproofing, through which the water percolates to

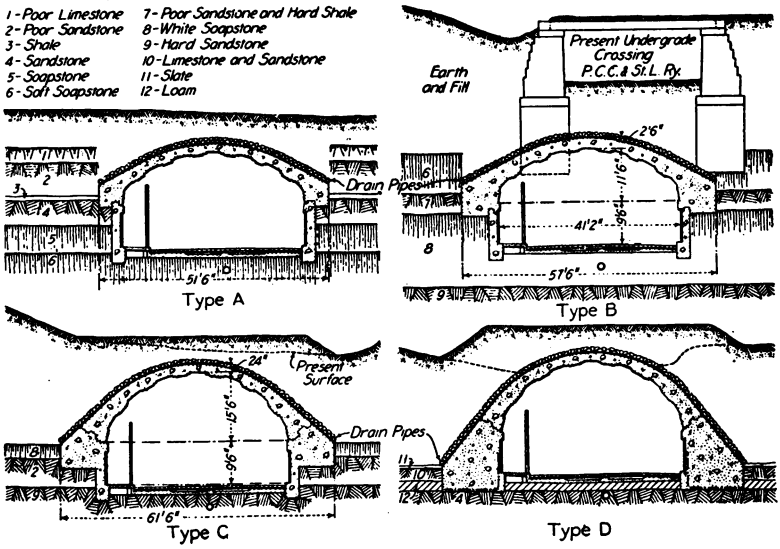


FIG. 197.—Typical cross sections of Corliss Street tunnel.

longitudinal terra-cotta pipes outside the springing lines on both sides of the tunnel. These connect under the floor slab with a full-length 15-in. terra-cotta pipe sewer located on the center line of the tunnel. The water collecting behind the high retaining walls also flows through broken stone drains to lines of horizontal terra-cotta pipes laid with open joints in clay on the wall footings.

The tunnel is divided into four sections with different types of lining, in which the thickness of the roof varies as required by the loading which comes upon it, and the side walls vary to conform

to the various strata encountered. In all types the intrados is a three-center curve. The change in height between the types was made necessary owing to the poor foundation for types *C* and *D*, Fig. 197, and the shallow headrooms for type *A*. The roof is connected to the side walls with a tongue-and-groove construction joint. Both side walls and arches are made throughout in longitudinal sections from 17 to 34 ft. long, separated by tongue-and-groove construction joints in vertical transverse planes. Beginning at one portal where the excavation is entirely through strata of different kinds of rock, there is a 135.5-ft. length under the Ohio Connecting Railroad and shallow covering, of type *A* lining, with thin side walls connected to the roof arch with horizontal construction joints at the springing lines. Owing to the concentrated loads from locomotives passing over this section, it was found necessary to use reinforcement in the roof arch.

Adjacent to type *A* there are 195.5 ft. of type *B* tunnel, located under the Pittsburg, Cincinnati, Chicago & St. Louis Railroad and deep embankment. This section has a thicker roof to carry the heavy loads which rest upon it. The construction joints between the roof arch and the side walls are placed at a little lower elevation in this type, and much heavier skewbacks are required to provide the required bearing for this type of tunnel.

Next there are 52 ft. of type *C* tunnel which is increased 4 ft. in height to reduce the horizontal thrust of the arch, thereby reducing the amount of concrete necessary for the footings of the side walls. The side walls are made very heavy, as the poor rock extends up along to the springing line, and the construction joint with the roof arch is made at an angle of 45° with the horizontal. The remaining 51 ft. of tunnel lining at the other portal are of type *D*. Very thick walls and abutments are necessary to transfer the thrust line of the arch to strata of sufficient abutting power to resist it. The extrados is tangent with the battered rear face of the side walls and the construction joint is normal to the thrust line of the arch.

INDEX.

A

Aare limestone, conductivity of, 124
Accidents during construction, 179, 193, 210
Acetylene lamps, carbon dioxide generated by, 148
  heat generated by, 148
  use of, 157
Adits, grade of, 11
  choice between adit and shaft, 12
  use of, 10
Aerology, 121
After coolers, 68
Air blowers, 160, 161, 162
  compressed, consumed by drills, 154
    by locomotives, 154
  compressors, capacity of, 68, 69
    type of, 69
  cooling of, 154
  drills, types of, 63
    weight of, 63
  gradient, at various elevations, 133
  locks, 205, 206
    Gattico tunnel, 206, 211
    East View tunnel, 217
    Milwaukee Waterworks tunnel, 216
  precoolers, 68
  pressure, in caissons, 205
    in locomotives, 91
    in ventilating pipes, 159, 160, 162
    in water injectors, 159
  refrigeration of, 154, 158
  vitiation of, by animals, 145
    by explosives, 146
    by men, 145
    by miscellaneous agencies, 149
Albula tunnel, drills used in, 157
American method, advantages and disadvantages of, 49, 53
  of blasting, 19
  of drilling bore holes, 15, 17
  of timbering, 53
  of tunnel driving, 171, 174
Antigorio Gneiss, thermal conductivity of, 125
Andesite, thermal conductivity of, 124
Arch centers, 56
  removable, 57
  of steel, 56, 118
Arizona shaft, Colorado siphon, 190
Arlberg tunnel, type of drills used in, 157
  ventilation of, 156
Artificial ventilation, tunnels driven without, 26
Austrian method of driving, 168
  of timbering, 169, 170
  new, 170
Auxiliary heading or bore, 4, 71
Average driving progress in headings, 76, 77, 83

B

Baltimore Belt-line tunnel, 167
Bar mounting for drills, 64
Belgian method, advantages and disadvantages of, 166
  of excavating, 165
  of lining, 166
  of timbering, 165
Bench, advantages and disadvantages of, 49
  method of excavating, 32, 45
    high bench, 46
    low bench, 46
Bends, 205
Blackwell tunnel, 188

Blasting caps, grade of, 19
methods, in the United States, 19
in Europe, 19
powder, use of, 20
Blaw steel forms, 39, 42
Bonticou tunnel, length of, 37
Borings, test, 186, 194, 198
Bosruck tunnel, 100
Box cars, 22, 23, 88, 89
Buffalo Waterworks tunnel, dimensions of, 10
explosive consumption in, 21
materials penetrated by, 19
Bureau of mines, acknowledgment, 29
Brandleite tunnel, explosive consumption, 15
progress per attack, 15
Brick masonry, use of, 110, 182
Bruggwald tunnel, 179

C

Cairasca Valley, 116
Caisson disease, 205
Caissons, Gattico tunnel, 211, 213
table of, 188
Calcareous schists and limestone, conductivity of, 125
Calcium carbide, combustion of, 148
Capacity of ventilating plants, 156, 158
of ventilation, 151, 152
Caps, blasting, 19
Carbon dioxide, effects of, 146
generated by men, 145
by animals, 145
by explosives, 146
by miscellaneous agencies, 149
proportion allowed for ventilation, 149
Carriages, drill, used in Loetschberg tunnel, 65
Mount Royal tunnel, 66
Cars, box, 22, 23, 88, 89
ice, 160
Cascade tunnel, cost of, 52
method of driving, 49
of lining, 59
Catskill Aqueduct tunnels, pressure tunnels, 42
method of excavation, 32
of lining, 42, 43
Caves in limestone formation, 115
Center cut method, 15, 16
Clay, weight per cu. ft., 176
angle of repose, 176
Colorado river siphon, 186
Column mounting for drills, 63, 64
Compressed air, use of, for locomotives, 89, 91
for ventilation, 153, 154
and Foundation Worker's Union, 207
Compressor plants, capacity, make, 68
Concrete blocks, use of, 117
linings, use of, 110
method of construction, 38, 42, 43
Consumption of explosives in heading work, 14, 15, 21
Cost of driving tunnels of small cross section, 28, 29, 30
lining small tunnels and tunnels of medium cross section, 39, 41
lining railroad tunnels, 62
railroad tunnels, 52
timbering railroad tunnels, 55
Crown bars, use of, 167, 170, 171
Current, electric, as source of power, 67
for firing blasts, 20

D

Depth of bore holes, 17
of bore holes to record ground temperature, 135, 136
overlying, influence of, 137
Determination of ground temperature, 138, 139
of air temperature, 133, 143
of stresses in lining, 113

Detonators, grade of, 19
Diesel engines, 67
Direction of bore holes, in headings, 16
in stoping work, 46
Distance center to center of bores, 4
Drainage canal, 117
of tunnel linings, 115
Drift method, use of, 50
advantages and disadvantages, 51
Drill carriages, 65, 66, 67
Drilling methods, 12
Drills, electric, 63
hydraulic, 64
mounting of, 63, 64
pneumatic, 63
Driving methods, American, 171
Austrian, 168
Belgian, 165
English, 167
German, 164
Italian, 170
long and deeply overlaid tunnels, 70
Driving tunnels with compressed air, 204
Dumping cars, 22, 23
devices, 23
Dynamite, consumption of, 15, 21
gases generated by, 147
kind of, 20

E

Earth, weight of, 176
angle of repose of, 176
Efficiency of bore holes, 17
American method, 17
European method, 14, 17
Electric detonators, 19
drills, 63
driven compressors, 67, 68
firing, 19
locomotives, 22, 23, 92
power, 67
Elizabeth Lake tunnel, cost per lin. ft., 29
driving methods, 31
Enlargement of top heading, 33, 34
of tunnel section, 34, 75, 76
Excavation, sequence of, Arthur Pass tunnel, 81
Cascade tunnel, 49
Karawanken tunnel, 75
Loetschberg tunnel, 69
Murray Hill tunnel, 51
Simplon tunnel, 78
St. Paul Pass tunnel, 46
Explosives, consumption of, 156
gases generated by, 147
heat generated by, 147

F

Failures of tunnel linings, Bosruck tunnel, 100
Gattico tunnel, 210
Karawanken tunnel, 101
Ricken tunnel, 99
Weissenstein tunnel, 99
Firing blasts, 19
Force, working, 92
Framing timber, cost of, 55
Fuse, safety, 20

G

Gallitsin tunnel, consumption of explosives, 21
drilling method, 48
materials penetrated by, 21
Gases encountered in Gunnison tunnel, 26
in Ricken tunnel, 99
Gasolene locomotives, 92
Gauge of track in tunnels, 88
Gelatine dynamite, 20
Geologists, names of noted, 120
Geology of Granges tunnel, 131
Gattico tunnel, 207
Hauenstein tunnel, 82
Hudson siphon, 194
Ricken tunnel, 99
Simplon tunnel, 2, 101
Weissenstein tunnel, 100
Geothermic gradient, value of, in bore holes, 121, 122

Geothermic gradient, under mountains, 123
under valleys, 122
German method of excavating, 164
of lining, 165
of timbering, 164
Giersky tunnel, area of, 26
Glasgow tunnel, shaft, 188
Gneiss, value of geothermic gradient, 126
Granges tunnel, compressor plant of, 69
driving progress in, 76, 80
lining of, 110
longitudinal section of, 131
rolling equipment of, 89
Granite, conductivity of, 125
value of geothermic gradient of, 126
Gravel, angle of repose of, 176
weight of, 176
Grouting, Catskill aqueduct pressure tunnels, 43
Hudson river siphon, 196
Tallulah Falls tunnel, 41
Gunnison tunnel, cost per lin. ft. of, 29
haulage method in the, 22
method of lining the, 38, 40
size of, 29
ventilation of, 25
Gun powder, 20

H

Hammer drills, weight of, 63
Handling excavated materials, 85
Hauenstein tunnel, driving progress at, 77
lining of, 111
longitudinal section of, 82
Haulage, by use of compressed air locomotives, 89, 91
electric locomotives, 23
gasolene locomotives, 92
steam locomotives, 89
Haulage, cost of, 24
methods, 22, 23, 88
Heading, cost of driving, 28, 29
method of driving, 9
size of, 10, 16
timbering of, 26
Heat generated by acetylene lamps, 148
consumption of explosives, 147
oil lamps, 148
Heat radiation of human beings, 148
Height of ellipse of pressure, 106
Holes (see Bore Holes).
Hoosac tunnel, reference to, 167
Horizontal bar mounting for drills, 84
Horse haulage, cost of, 24
Hudson river siphon, driving methods, 195
geology of, 194
shafts of, 195
Humidity in tunnels, percentage of, 148
Hunters Brook tunnel, cost of driving, 33, 34
driving method, 32
Hydraulic drills, use of, 64
turbines (see Water Wheels).

I

Ice cars, 160
Illumination of tunnels, 157
Influence of water, on the geothermic gradient, 127
on the rock temperature, 128
Information required to determine ground temperature, 120
Injectors, 159
Interest charges during construction, 77
Internal combustion engines, 67
Invert, masonry, 118
Iron linings, 188
Italian method, sequence of excavation, 171
driving method, 170

J

Jackhammers, use of, 63
Joachim Valley, mines of, 124

Joker tunnel, size of, 10
Jungfrau tunnel, method of mounting drills, 64
type of drills used in, 64

K

Kaiser Wilhelm tunnel, 86, 87
Kandergrund tunnel, explosive consumption, 21
Karawanken tunnel, driving method, 74, 75
ground pressure in, 101
Kertish Town, value of geothermic gradient, 122
Kubel tunnel, explosive consumption, 21

L

Labor, cost per cu. yd., for concrete, 41
for excavation, 29, 30, 34, 37
for masonry, 62
Labor cost, per lin. ft. of tunnel, 29, 30, 52, 62
Lamps, acetylene, 157
Laramie Poudre tunnel, cost per lin. ft., 29
size of, 10
ventilation of, 24
Lausanne tunnel, depth of bore holes, 19
size of, 10
Length of bore holes per cu. yd., 18
of tunnels of small and medium cross section, 37
Lining a timbered tunnel with concrete, 57
cost of, 51
deep tunnels, 108
determination of stresses in tunnel linings, 113
of the Bruggwald tunnel, 180
of the Gattico tunnel, 213
of the Granges tunnel, 110
of the Hauenstein tunnel, 111
of the Loetschberg tunnel, 111
Lining of the Mont d'Or tunnel, 111
of the Ricken tunnel, 109
of the Simplon tunnel, 71
of the Weissenstein tunnel, 109
of the Yuma siphon, 187
railroad tunnels of moderate length, 56
the Cascade tunnel, 59
the Gunnison tunnel, 38
the Musconetcong tunnel, 56
the pressure tunnels of the Catskill Aqueduct, 42
the Tallulah Falls tunnel, 39
tunnels on the Grand Trunk Pacific, 60
tunnels of small and medium cross section, 38
Little Tom tunnel, cost of, 52
Loading, method of loading bore holes, 19
Location of bore holes, in headings, 15
of observation stations, 133
size and number of bores, 3
Locomotives, 23, 89, 90, 92
Loetschberg tunnel, driving method, 79
driving progress in, 77, 80
explosive consumption in, 21
humidity in, 149
lining of, 111
mucking method in, 86
size of heading, 10
ventilation of, 160
Long and deeply overlaid tunnels, 70
Lucania tunnel, cost per lin. ft., 29
depth of bore holes in, 19
size of, 10

M

Maps, geographical, 121
Marne ship canal, 221
Marshall Russell tunnel, size of, 10
Masonry brick, 110, 182
linings, 110
stone, 110
Material, tunnels driven through soft, 163

Mauvage tunnel, 221
Melones Mines, materials penetrated, 18
Method, top and bottom heading, 46, 74
top heading and bench, 45
Methods of driving tunnels, 9, 31, 45
haulage, 22, 23, 88
Milwaukee Waterworks tunnel, 215
Miscellaneous tunnels, 218
Monthly driving progress, 79
Mont d'Or tunnel, lining of, 111
Moodna pressure tunnel, materials penetrated, 19
size of heading, 19
Mount Royal tunnel, drill carriage used at, 19
lining of, 112
size of heading, 19
Mucking methods, 85, 221
Muck pile, shape of, 19
Murray Hill tunnel, sequence of excavation, 51
timbering method at, 55

N

Natural ventilation, tunnels driven without, 26
Newcastle coal fields, 122
Newhouse tunnel, size of, 10
New Raton tunnel, cost of, 52
Nisqually tunnel, depth of bore holes, 19
size of tunnel, 19
Nitroglycerine dynamite, 20
burning temperature of, 147
Number of bore holes in headings, 15, 16, 17
of drills used in various tunnels, 15

O

Observation stations, location of, 134
Oneida tunnel, depth of bore holes, 19
size of, 19
Open cut, 45
Ore, deposits, 126
Overlying depth, 137
Oxidation, heat generated by, 126
Oxygen, 145

P

Para gneiss, conductivity of, 124
Percentage of cores recovered, 198
Pfaffensprung tunnel, 26
Phyllite, value of geothermic gradient, 124
Pikes Peak, elevation of, 133
Pilot tunnel, 74
Pipes, for ventilation, size of, 25, 157
Pneumatic drills, 63
Pontis limestone, 124
Power and compressor plants, 68
electric, 67
steam, 67
water, 67
Prato tunnel, 26
Precoolers, 68
Pressure, air, for compressed locomotives, 91
for caisson work, 205
for ventilation, 159, 160
Pressure, ground, 97
Progress, driving, per attack, 15
per month, 83
per quarter, 76
Progress, for lining tunnels, 76
Protogine, value of geothermic gradient, 126
Pyramidal cut, 16

Q

Quantity of air for ventilation, 156
Quartz, conductivity of, 124
mica schist, conductivity of, 124

R

Railroad tunnels of moderate length, 45
cost of, 52
cost of driving, 52
cost of lining, 62
cost of timbering, 55

Rawley tunnel, cost of, 29
size of, 10
Refrigeration, of the Simplon tunnel, 159
of tunnels during construction, 154
Rehberg tunnel, length driven without artificial ventilation, 26
Relining the Mauvage tunnel, 221
Ricken tunnel, ground pressure in, 99
length driven without artificial ventilation, 26
lining of the, 109
longitudinal geological section, 99
size of drainage conduit, 118
Rock drills, electric, 63
hydraulic, 64
pneumatic, 63
Rock temperature, computation of, 143
determination of, 120
influence of water on, 128
Rofna porphyry, value of geothermic gradient, 124
Rondout siphon, driving the, 202
geological formation of the, 200
method of construction, 202
practical questions with reference to the, 200
Roosevelt tunnel, cost per lin. ft., 29.
length of, 37
size of, 19
Rubble masonry, 110
Ruhr coal fields, value of geothermic gradient, 122
Russel tunnel, type of drills used at, 64

S

Saarbrucken mines, value of geothermic gradient, 122
Safety fuse, use of, 20
Sandstone, value of geothermic gradient, 120
Schist, conductivity of, 125
value of geothermic gradient, 126
Schladebach, value of geothermi gradient, 124
Sella gneiss, conductivity of, 125
Shafts, 188, 192, 208, 211
Shaft sinking, 190, 192, 20.
Shale, value of geothermic gradient, 126
Simplon tunnel, consumption of explosives in, 15
drills used at, 64
driving method, 78
geological section, 2
lining of, 71
locomotives used at, 89
method of haulage, 85
refrigeration of, 158
rock temperature in, 2, 139
size of heading of, 10
ventilation of, 157, 158
Siphon tunnels, Colorado River siphon, 186
Croton Lake siphon, 196
Hudson River siphon, 194
Size of concrete blocks, 117
timber sets, 27
ventilating pipes, 25, 157
Snow, use of, 162
St. Gothard tunnel, length of, 71
value of geothermic gradient, 123
St. Paul pass tunnel, cost of driving, 51
cost per lin. ft., 55
cost of timbering, 55
driving progress, 48
Stampede tunnel, cost of, 52
Steam shovel, use of, 47, 50
Steel plates, for mucking, 86, 221
Stillwell tunnel, cost of, 29
Stoping method, 33, 46
Storage battery locomotives, cost of haulage with, 24
use of, 22, 23
Strawberry tunnel, cost of driving, 29
haulage method, 22
length of, 37
materials penetrated, 19
size of, 10

Strickler tunnel, 68
Sutro tunnel, 18

T

Tallulah Falls tunnel, cost of driving heading of, 36
cost of excavation, 41
cross section of, 35
Tamping bore holes, 19
Tauern tunnel, ventilation of, 156
Temperature, air, 132, 135
in bore holes, 122
ground, 132, 135, 139
in tunnels, 134, 156
Tequiquac tunnel, 18
Timbering, cost of, 55
headings and tunnels of small cross section, 26
long and deeply overlaid tunnels, 94
railroad tunnels of moderate length, 53
type of, 54, 55
Top heading and bench method, 32, 45
advantages and disadvantages of, 49
Tunnel cars, 22, 88, 89
headings, size of, 10
Tunnels, driven through soft materials, 163
driven with compressed air, 204
long and deeply overlaid, 70
miscellaneous, 218
siphon, 185
Turbo compressors, 67

U

Underground water, 3, 7, 116, 130
Underpinning, masonry arch, 166
United States Geological Survey, data collected by, 121
United States Weather Bureau, records of the, 121, 143

V

Value of geothermic gradient, 121
Variation of geothermic gradient with depth, 127
Velocity of water through nozzles, 159
Ventilation, during construction, 158
of the Loetschberg tunnel, 160
of the Simplon tunnel, 157
of tunnels of small cross section, 24
secondary, 160, 162
size of pipes for, 157
Vertical column, for drill mounting, 63, 64
Vitiation of the atmosphere, 145

W

Walkill pressure tunnel, compressor plant of, 68
explosive consumption per cu. yd. in, 21
size of heading of, 19
Water, conveying tunnels, 9
power, 67
underground, 3, 116, 130
Waterproofing tunnel linings, 117
Webster tunnel, cost of, 52
Weissenstein tunnel, geological cross section, 100
ground pressure in, 99
ground temperature in, 129
lining of, 109
Wet clay, weight of, 176
earth, weight of, 176
sand, weight of, 176

Y

Yakoust, value of geothermic gradient, 122
Yearly average air temperature, 121, 132, 136
ground temperature, 121, 136
Yuma irrigation project, 186

CR
JL